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Vehicle-cycle Inventory for Medium- and Heavy-duty Vehicles

Energy Systems Division

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ACRONYMS

ADR	Assembly, disposal, and recycling
Argonne	Argonne National Laboratory
BatPaC	Battery performance and cost
BC	Black carbon
BMS	Battery management system
CAFE	Corporate average fuel economy
CI	Compression ignition
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
DoT	U.S. Department of Transportation
EPA	U.S. Environmental Protection Agency
EV	Electric vehicle
FCV	Fuel-cell (electric) vehicle
GHG	Greenhouse gas
GREET®	Greenhouse gas, Regulated Emissions, and Energy Use in Transportation)
HDPE	High-density polyethylene
HEV	Hybrid electric vehicle
HVAC	Heating, ventilation, air conditioning
ICEV	Internal combustion engine vehicle
lbs.	Pounds
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
LCA	Life-cycle analysis
LDV	Light-duty vehicles
Li-ion	Lithium-ion
MHDV	Medium- and heavy-duty vehicle
mmBtu	1 million British thermal unit
N_2O	Nitrous oxide

NMC	Nickel-manganese-cobalt
NO_X	Nitrogen oxide
OC	Organic carbon
OEM	Original equipment manufacturers
Pb-acid	Lead-acid
$PM_{2.5}$ or PM_{10}	Particulate matter
PnD	Pickup and delivery
PE	Polyethylene
PET	Polyethylene terephthalate
PFSA	Perfluoro sulfonic acid
PP	Polypropylene
PPS	Polyphenylene sulfide
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
SA	Strategic analysis
SO_2	Sulfur dioxide
SO_X	Oxides of sulfur
VOCs	Volatile organic compounds
W/kg	Watt per kilogram
Wh/kg	Watt-hour per kilogram
wt.%	Percentage by weight
WTW	Well-to-wheel

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1 INTRODUCTION

The United States has witnessed multiple attempts to improve fuel economy and reduce pollutant emissions in the transportation sector, guided chiefly via technological interventions by original equipment manufacturers (OEMs) and by specific policies of the U.S. Federal Government, like Corporate Average Fuel Economy (CAFE) norms (Burnham et al., 2006; U.S. DoT, 2013). These efforts have resulted in the growing adoption of alternatives to conventional materials, fuels, and vehicle propulsion technologies across various transportation modes, while also helping to lower global pollution (greenhouse gas, or GHG, emissions). Yet, a holistic evaluation of the ecofriendliness of these alternatives, particularly their energy use and emissions, merits detailed focus on their entire life-cycle, and thereby, on the life-cycle of associated transport modes. This is vital since alternative fuels and materials can differ vastly in energy sources and production methods employed for their processing vis-à-vis their existing counterparts — and this difference causes significant variation in their respective upstream emissions.

Over the last three decades, the Energy Systems Division at Argonne National Laboratory has undertaken the aforementioned task through life-cycle analysis (LCAs) of light-duty vehicles (LDVs), inclusive of both transportation fuels and vehicle technologies (Burnham, 2012; Burnham et al., 2006). Argonne's GREET® (Greenhouse gas, Regulated Emissions, and Energy Use in Transportation) model is both a product of and a tool for these analyses (Argonne National Laboratory, 2020). GREET® has been used to determine and analyze energy and emission impacts of different energy sources over their entire life-cycles [i.e., fuel-cycle or well-to-wheel (WTW)]. Further, the model has expanded to encompass extraction, processing, production, and refining of prominent materials in desired forms, including metals, plastics, and composites. This has enabled researchers to use GREET® for LCAs of numerous energy sources and for advanced technologies across multiple sources, including but not confined to the transport sector.

Apart from LDVs, a key contributor to total energy consumption and emissions emanating from the transportation sector is freight transport, especially its road-based aspect (U.S. DOE, 2021; U.S. EPA, 2021), despite freight trucks constituting a small share of on-road vehicles (Davis & Boundy, 2021). Hence, Argonne has identified the need to conduct LCA for on-road freight transport. GREET® already has the data that has been used to conduct WTW analysis of medium- and heavy-duty vehicles (MHDVs) (Argonne National Laboratory, 2020). However, it does not have the associated vehicle material burdens needed for cradle-to-grave analysis of MHDVs. This is a key requirement, as unlike LDVs, MHDVs require substantially more materials across different components, including for van/boxes and heavy-duty trailers, to ensure safe and reliable housing and transport of heavy goods. Also, MHDVs have considerably lower fuel economy than LDVs (Davis & Boundy, 2021), leading to significant fuel use and emissions for them. Together, these factors increase the energy use and emissions of MHDVs over LDVs during their life-cycle stages, whether it be manufacturing of materials and components, component assembly and vehicle production, vehicle operation, or the recycling/disposal of vehicle components.

Over the past decade, MHDVs have seen an increasing interest in alternative fuels and propulsion technologies, akin to LDVs (Burke & Sinha, 2020; Forrest et al., 2020; Kluschke et al., 2019). Researchers have investigated the replacement of diesel powertrains with alternative technologies, including hybridization, battery electric, and fuel-cell MHDVs (Cunanan et al., 2021; Kluschke et al., 2019). There has also been an effort to shift away from conventional diesel toward other fuels, such as compressed natural gas, biofuels, and e-fuels (Bicer & Dincer, 2018; Kluschke et al., 2019; Osorio-Tejada et al., 2017). At the same time, there has been a growing focus on improving powertrain efficiency of diesel trucks, developing novel after-treatment technologies to meet increasingly stringent emission norms, and lightweighting MHDVs to increase their fuel economy (Joshi, 2020; Kluschke et al., 2019; Rodríguez et al., 2017). Together, these trends have led to the incorporation of newer materials and components in MHDVs, with considerable variation in their energy and emission effects over their previously used counterparts.

The aforementioned trends and observations necessitate a thorough investigation of energy use and emissions of MHDVs over their *entire* life-cycle — encompassing major powertrain technologies, key materials, and aspects critical to this sector — to determine their overall environmental performance. This need is addressed here in this report through the description of a vehicle-cycle model that has been developed for MHDVs in GREET®. Apart from providing energy and emission impacts of vehicle technologies and fuels, the model enables researchers to modify input assumptions and obtain energy use and emissions for user-defined MHDV types, MHDV material composition, and the nature of the fuel used (diesel, electric, etc.). The model also allows researchers to modify input assumptions related to upstream emissions of fuels (e.g., grid mix for electricity used in battery electric MHDVs, etc.) and assess their effects on MHDV energy use and emissions.

The rest of this document is organized as follows. Section 2 presents a brief literature review of the previously conducted studies. Section 3 provides a description of our modeling approach, specifications of MHDVs considered in this study, and a discussion on the processes and corresponding data inputs for MHDV component production. Section 4 provides a brief description of vehicle assembly, and end-of-life (recycling/disposal of their components). Finally, Section 5 presents the model structure used for MHDVs in the updated GREET® model and is followed by the references used in this study.

2 LITERATURE REVIEW

While fewer LCAs have been conducted for MHDVs compared to LDVs, a number of MHDV LCAs have been undertaken over the last decade (Machado et al., 2021; Sen et al., 2017). However, these studies have focused primarily on WTW analysis of fuels used for MHDVs (i.e., fuel-cycle analysis). This is because their main goal is to determine the environmental benefits (reduction in GHG and local pollutant emissions) of switching from conventional diesel to alternative fuels, such as natural gas, biofuels, electricity, and hydrogen. Among the remaining studies, some focus on the vehicle-cycle of buses (Sen et al., 2017). In contrast, only a few studies analyze the vehicle-cycle of freight-based MHDVs due to the dearth of inventory data for these vehicles in literature. These studies are discussed below in detail to provide the context and the need for the present work.

A vehicle-cycle analysis of MHDVs by Gaines et al. (1998) was conducted more than two decades ago. This study represents an early attempt to construct a detailed inventory for MHDVs towards conducting their process-based LCA. At the time of their study, the authors analyzed both the then-existing and advanced versions of Class 8 tractor-trailer trucks based on diesel (petroleum and Fischer-Tropsch) and liquefied natural gas. In their study, they highlight the dominance of iron, steel, and wrought aluminum in the material composition of these trucks while also discussing possibilities for MHDV lightweighting that could be achieved via use of aluminum and magnesium. Further, Gaines et al. (1998) conduct LCA of all the chosen Class 8 MHDVs and highlight the modest contributions from the vehicle-cycle to overall MHDV energy use and GHG emissions due to the predominant role of the fuel-cycle stage (vehicle operation, and fuel production and distribution). However, they also show the significant effect of the vehicle-cycle on four MHDV pollutant emissions on life-cycle basis: particulate matter (PM_{10}), oxides of sulfur (SO_X), volatile organic compounds (VOC), and methane (CH_4). Yet, given the significant passage of time since the publication of this report and the substantial efforts undertaken by OEMs since then to lightweight MHDVs, the inventory here cannot be considered to represent the modern-day MHDVs and thus needs updating.

Four studies (Sen et al., 2017; Zhao et al., 2016; Zhao & Tatari, 2017; Zhou et al., 2017) constitute another set of literature on the vehicle-cycle of MHDVs. All these studies encompass the vehicle-cycle of MHDVs for different types of vehicles: Class 6 medium-duty trucks (Zhou et al., 2017), refuse collection trucks (Zhao & Tatari, 2017), Class 8 heavy-duty trucks (Sen et al., 2017), and Class 4 trucks (Zhao et al., 2016). Along with the variation in the types of vehicles, two common themes emerge from these studies: their comparison of battery electric and diesel trucks, and the use of an economic input/output LCA approach to calculate the vehicle-cycle energy use and emissions. Overall, these studies highlight the benefits of truck electrification over conventional diesel trucks and the low influence of vehicle and battery manufacturing to the overall MHDV life-cycle energy use and emissions. However, the use of an input/output LCA approach negates the need to develop a detailed life-cycle inventory of MHDVs, thus leading to the lack of a recent inventory for their vehicle-cycles. This makes it difficult to assess if the impacts of vehicle production are indeed as low or negligible, as indicated in these four studies.

The most recent work on the vehicle-cycle of MHDVs was conducted by Wolff et al. (2020) for multiple types of trucks to precisely address this gap on the lack of detailed inventory. However, due to the lack of sufficient literature on this subject, Wolff et al. (2020) used a number of references for weight and material composition of different MHDV component systems, including frame rails and cabs, chassis, and wheels and tires. They also scaled up the weight of several components (such as engines) by using the weight of the corresponding/analogous components in LDVs due to the paucity of publicly available data for these components. This makes it difficult to ensure that only MHDVs of similar performance across different powertrains (e.g., diesel, electric, and fuel-cell trucks) are being compared.

In sum, this review highlights the gap of a detailed MHDV vehicle-cycle inventory, which is essential to analyze its environmental impact for different powertrains and use these results to evaluate their overall life-cycle performance. The subsequent chapters focus on steps followed to create such an inventory as well as the final inventory developed from this exercise.

3 MODELING APPROACH AND VEHICLE SPECIFICATIONS

3.1 Modeling Approach

The modeling approach used previously for LDVs in GREET® (Burnham, 2012; Burnham et al., 2006) has been extended to MHDVs here. Broadly, two energy cycles are considered to assess MHDV energy use and emissions: vehicle-cycle and fuel-cycle. The vehicle-cycle encompasses vehicle extraction, processing, and fabrication; component production (from materials) and their assembly to manufacture trucks; and end-of-life (recycling/disposal) of truck components. The fuel-cycle consists of production, storage, and distribution of primary energy and fuel, along with vehicle operation (fuel use for driving). Since MHDV energy use and emissions during the fuel-cycle are already established in GREET® (Argonne National Laboratory, 2020), these are directly used in this study, with the rest of this report focusing on vehicle-cycle modeling.

Like for LDVs, all the primary and secondary energy forms used in processes comprising the different vehicle-cycle stages are converted to final primary energy usage and emissions to provide a life-cycle perspective. For emissions, three GHGs (CO_2, CH_4, and N_2O) and eight pollutants (VOCs, CO, NO_X, SO_2, PM_{10}, $PM_{2.5}$, BC, and OC) are computed based on in-built fuel and process characterization factors in GREET® (Argonne National Laboratory, 2020). Both emissions (total and urban) and water consumption are calculated for all vehicle-cycle related processes. All background calculations for LCA, derive from the existing GREET® model, that are well established and documented (Argonne National Laboratory, 2020).

The focus of this study is on determining the amount of each material used in MHDVs over their lifetime. For this, weights of prominent MHDV component systems are multiplied with their respective material composition, while accounting for the replacement of individual parts within these systems during the MHDV lifetime. Component systems considered here include: (a) systems that are common with the GREET® model for LDVs, such as body, chassis, powertrain, transmission, batteries, electric drive components (such as motor, electronic controller, and generator), fuel-cell hydrogen tank storage systems or fuel-cell onboard storage, and fluids; and (b) additional freight-specific systems that are used only in MHDVs, such as van/box, trailer, and lift-gates. Based on the materials used in these systems, the vehicle-cycle model (GREET2) calculates energy consumption and emissions across all its constituent processes. These effects, calculated for different component systems, are segregated, and grouped into five component categories: *vehicle components, batteries, fluids, trailers,* and the combined processes of *truck assembly, painting, disposal, and recycling* (ADR). Note that energy use and emissions for fluids and ADR processes employed for trailers are considered within the *trailers* category itself.

For most component systems in the vehicle-cycle, their definition for MHDVs is similar to that for LDVs in GREET® (Burnham, 2012; Burnham et al., 2006). Freight trucks employ additional fluids compared to those required for LDVs, prominent among which are lubricant oils (used for axle, driveshaft, inter-axle shaft, and wheel-ends) and coolant cleaners (used along with engine/powertrain coolant). Hence, the *fluids* group in this work expands beyond that for LDVs to include these additional fluids/lubricants.

3.2 Vehicle Specifications

Three MHDV options are considered in this study: a Class 6 pickup-and-delivery (PnD) truck, a Class 8 regional day-cab truck, and a Class 8 long-haul sleeper-cab truck. In the GREET1 Excel model, these are respectively referred to as follows: MHD vocational vehicle (Class 6 PnD truck), combination short-haul truck (Class 8 day-cab truck), and combination long-haul truck (Class 8 sleeper-cab truck). Three propulsion technologies are evaluated for these options: an internal combustion engine vehicle (ICEV) that uses a compression-ignition (CI) diesel engine; a battery electric vehicle (EV); and a fuel-cell electric vehicle (FCV) with hybrid configuration. In addition, for the Class 6 PnD truck, this study also includes a fourth propulsion technology in the form of a grid-independent hybrid electric vehicle (HEV) that is based on a CI diesel engine as primary source.

3.3 Total Vehicle Weight

Table 1 shows the total vehicle weights for all MHDVs and propulsion technologies that are considered in this study (excluding fuel). These weights correspond to the values provided for corresponding MHDVs in Autonomie simulations (Argonne National Laboratory, 2021).

Table 1 Total vehicle weight for MHDVs including fuel (lbs.)

MHDV type	ICEV	HEV	EV	FCV
Class 6 PnD	16,984	17,120	19,177	16,654
Class 8 day-cab	16,631	16,897	23,721	17,457
Class 8 sleeper-cab	18,216	18,481	32,017	21,337

For each of the chosen MHDVs, total vehicle weight is disaggregated into four of the five above-mentioned component categories: *vehicle components, batteries, fluids,* and *trailers*. Among these, *vehicle components* consist of ten key subsystems: truck body, chassis, transmission, powertrain, generator, traction motor, electronic controller, van/box, lift-gates, and fuel-cell onboard storage (or hydrogen tank storage system for fuel-cell trucks). Not every propulsion technology uses all of these components. For instance, while the ICEV employs only truck body, chassis, powertrain, and transmission, the HEV is a parallel hybrid truck that uses motor, electronic controller, and engine (diesel engine as primary source). Similarly, Class 6 PnD trucks use a van/box attached to the chassis, while Class 8 trucks use trailers that can be attached and detached from the chassis using a fifth-wheel. It is for this reason that the van/box is included within the *vehicle components* category, while *trailers* are considered a separate category (included in “Others” within the GREET.Net model). Lastly, an electric motor powers both EV and FCV MHDVs, with the FCV being a hybrid truck model that uses a fuel-cell and battery as its primary and secondary energy sources, respectively.

Like LDVs, freight trucks also employ batteries for vehicle startup and accessory loads. Across all MHDVs and propulsion technologies, the base battery is lead-acid (Pb-acid). Apart from this, a lithium-ion (Li-ion) battery is provided as a traction battery in HEV, EV, and FCV MHDVs. Conversely, as stated earlier, *fluids* used in MHDVs expand beyond those used in LDVs to include engine oil, lubricant oils (used for steer and drive axles, inter-axle shaft, driveshaft, and wheel-ends at both axles), power steering fluid/oil, engine/powertrain coolant with coolant cleaner, transmission fluid, brake fluid, windshield fluid, and adhesives. *Trailers* consist of several parts that are categorized into three groups in this study: trailer body, chassis (includes trailer axle with brakes, suspensions, wheels, and tires), and auxiliary components or parts. *Trailers* also include fluids that are used specifically for their chassis (lubricant oils for the trailer axle and its wheel-ends) as well as ADR processes employed for trailer manufacturing.

3.4 Definition of Vehicle Components

As in LDVs, freight trucks use multiple parts that are aggregated into different component systems (Table 2), which is in line with the prior GREET® work on LDVs (Burnham, 2012; Burnham et al., 2006). Apart from the total vehicle weight, it is the weight (and material composition) of these systems that is relevant in evaluating and comparing the environmental outcomes of MHDV vehicle-cycles.

Table 2 Component systems/categories included in GREET2 for MHDVs

Component System	ICEV	HEV	EV	FCV
Truck Body	✓	✓	✓	✓
Chassis	✓	✓	✓	✓
Transmission	✓	✓	✓	✓
Powertrain	✓	✓	✓	✓
Traction Motor		✓	✓	✓
Generator		✓		
Electronic Controller		✓	✓	✓
Fuel-cell Onboard Storage				✓
Batteries	✓	✓	✓	✓
Fluids (excluding fuel)	✓	✓	✓	✓
Trailers	✓	✓	✓	✓

In this context, we use Autonomie — a simulation tool for vehicles developed by researchers at Argonne (Argonne National Laboratory, 2021; Islam et al., 2021). Autonomie calculates various characteristics of vehicles across all weight classes (Class 1–8) via use of several parameters, including powertrain/engine maps, different performance inputs, and drive cycles. These characteristics include, but are not confined to, total vehicle weight and weight breakup of vehicle component systems, vehicular fuel economies, and power/energy/sizing needs for batteries across different vehicles (by powertrain and weight class). This provides an opportunity to use these values to inform vehicle component sizing here and, thereby, compare MHDVs of equivalent performance across different powertrains (i.e., like-for-like comparison). However, the component systems used in Autonomie and their definitions differ from those used in this analysis (Table 3). To resolve this divergence, a combination of bottom-up and top-down approaches were used to determine the weight of all the component systems chosen in this work (Table 2).

Table 3 Component systems used here and in Autonomie

Systems: Autonomie	Systems: This Study
Chassis	Chassis (includes steer and drive axles, brakes, suspensions, driveshaft, inter-axle shaft, wheels, and tires) Truck body Box/Van/Trailer Lift-gates and Vehicle fluids Powertrain (After-treatment technology)
Powertrain (ICEV/HEV)	Powertrain (ICEV/HEV engine)
Transmission	Transmission (clutch, gearbox, and final drive)
Generator	Electric drive components (generator)
Motor	Traction motor and electronic controller
Batteries	Batteries (Pb-acid and Li-ion)
Fuel Tank	Powertrain (fuel tank)
Hydrogen Tank	Fuel-cell onboard storage
Fuel Cell	Powertrain (fuel-cell stacks)

The need for a bottom-up approach arises from two reasons. First, it is vital in determining the material composition for each component system, and thereby, for all MHDVs across different propulsion technologies. This is relevant since the amount of material use affects energy use and emissions of trucks, as highlighted earlier. Also, the bottom-up approach ensures that for all the component systems in MHDVs (Table 2), their constituent subsystems and individual parts are included within vehicle-cycle calculations. This is important as GREET® users are not presented with any of the individual subsystems or parts, but only the information about final component systems (Table 2).

To implement this bottom-up approach, Tables 4–13 provide the definitions of all the component systems considered in this study. For most systems, their definitions extend from Argonne's earlier work on LDVs (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006) due to similarity in constituents across both transport modes. Components that are employed only in MHDVs (van/box/trailer and lift-gates) are defined separately in terms of their constituent subsystems and individual parts (Tables 11–13). Additionally, the truck body includes sleeper-related components for Class 8 sleeper-cab trucks (Table 4), while chassis includes a fifth-wheel used to detach and attach *trailers* to Class 8 trucks (both day-cab and sleeper-cab trucks; Table 7). On similar lines, the *fluid* system in MHDVs encapsulates the expanded set of fluids mentioned earlier (Table 10). Based on these definitions, the weight of each component system was derived using bottom-up calculations.

Table 4 Body system

Subsystems	Description of Individual Parts
Cab-in-white	Primary MHDV structure, i.e., a single-body assembly to which the other major components are attached
Body Panels and Fairings	Closure and hang-on panels, including hood, roof, decklid, doors, quarter panels, and fenders, as well as fairings
Front/Rear Bumpers	Impact bars, energy absorbers, and mounting hardware
Glass	Front windshield, and windows (door, side, and sleeper)
Lighting	Exterior: Head lamps, fog lamps, turn signals, side markers, front top markers, and rear light assemblies Interior: Wiring and controls for interior lighting, instrumentation, and power accessories
Heating, Ventilation, Air Conditioning (HVAC) Module	Air flow system, heating system, and air conditioning system (includes a condenser, fan, heater, ducting, and controls)
Seating and Restraint System	Seat tracks, seat frames, foam, trim, restraints, anchors, head restraints, arm rests, seat belts, tensioners, clips, air bags, and sensor assemblies
Door Module	Door insulation, trim assemblies, speaker grills, and switch panels and handles (door panels are part of body panels)
Instrument Panel	Panel structure, knee bolsters and brackets, instrument cluster (including switches), exterior surface, console storage, glove box panels, glove box assembly and exterior, and top cover
Trim and Insulation	Emergency brake cover, switch panels, ash trays, cup holders, headliner assemblies, overhead console assemblies, assist handles, overhead storage, pillar trim, sun visors, carpet/rubber, padding, insulation, and accessory mats
Sleeper-cab	Meant for Class 8 sleeper-cab trucks, consisting of sitting and sleeping area with space for other amenities (microwave, refrigerator, etc.)
Body Hardware	Miscellaneous body components

Table 5 Powertrain system

Subsystems	Description of Individual Parts
Engine Unit	Engine block, cylinder heads, shafts, fuel injection, engine air system, ignition system, manifolds, alternator, containers and pumps for the lubrication system, gaskets, and seals
Fuel-cell Stack	Membrane electrode assembly, bipolar plates, gaskets, current collector, insulator, outer wrap, motor and motor controller, humidifier, coolant reservoir and pumps, radiator, sensors, valves, and tie bolts
Engine Fuel Storage System	Fuel tank, tank mounting straps, tank shield, insulation, filling piping, and supply piping
Powertrain Thermal System	Water pump, radiator, and fan
Exhaust System	Catalytic converter, muffler, heat shields, and exhaust piping
Powertrain Electrical System	Control wiring, sensors, switches, and processors
Emission Control Electronics	Sensors, processors, and engine emission feedback equipment

Table 6 Transmission system

Subsystems	Description of Individual Parts
Transmission Unit	Clutch, gear box, final drive, and controls Use of automated manual transmission system

Table 7 Chassis system

Subsystems	Description of Individual Parts
Cradle	Frame assembly, front rails and cross-members, and cab and body brackets (the cradle bolts to cab-in-white and supports the mounting of engine or fuel-cell)
Driveshaft/Axle/ Inter-axle Shaft	Propeller shaft that connects gearbox to the differential Half shaft that connects wheels to the differential Shafts that connect front and rear parts of a tandem drive axle
Axles	Steer (single) and drive (tandem) axles
Differential	A gear set that transmits energy from driveshaft to axles and allows for each of the driving wheels to rotate at different speeds while supplying them with an equal amount of torque
Suspensions	Upper and lower shock brackets, shock absorbers, springs, steering knuckle, and stabilizer shaft
Braking System	Hub, disc, rotor, splash shield, and calipers
Wheels and Tires	Steer and drive axle wheels and tires
Fifth-wheel	Fifth-wheel (used in Class 8 trucks)
Auxiliary	Steering wheel, column, joints, linkages, bushes, housings, and hydraulic-assist equipment

Table 8 Electric drive system

Subsystems	Description of Individual Parts
Generator	Power converter that takes mechanical energy from the engine and produces electrical energy to recharge batteries and power the electric motor for series HEV (not used in this study, as the HEV is a parallel HEV MHDV)
Traction Motor	Electric motor used to drive the wheels
Electronic Controller	Power controller/phase inverter system that converts power between the batteries and motor/generators for electric drive vehicles
Fuel-cell Auxiliary Components (fuel-cell onboard storage)	Compressed hydrogen tank system, tank liner and boss, dome protection, in-tank valve, regulator, housing and support, and other balance of plant (systems for water supply, air supply, cooling, and piping)

Table 9 Battery system

Subsystems	Description of Individual Parts
ICEV	Pb-acid battery to handle startup and accessory load
HEV, EV, and FCV	Pb-acid battery to handle mainly startup load Li-ion battery for use in electric drive system

Table 10 Fluid system

Subsystems	Description of Individual Parts
ICEV and HEV	Engine oil, engine/powertrain coolant with coolant cleaner, brake fluid, windshield fluid, transmission fluid, power steering fluid, lubricant oils, and adhesives
EV and FCV	Powertrain coolant with coolant cleaner, power steering fluid, brake fluid, transmission fluid, windshield fluid, lubricant oils, adhesives

Table 11 Trailer system

Subsystems	Description of Individual Parts
Body	Front, sides, floor, and roof of trailers
Chassis	Axles, suspensions, brakes, and shafts
Auxiliary	Trailer components not covered in body and chassis, such as landing gear, trailer bumpers, lighting, and mudflaps

Table 12 Van/Box system

Subsystems	Description of Individual Parts
Body	Front, sides, floor, and roof of van/box, along with auxiliary parts

Table 13 Lift-gates system

Subsystems	Description of Individual Parts
Lift-gates	Gates used for loading/unloading of goods, along with their hydraulic systems and other constituent parts

A top-down approach was subsequently employed to use Autonomie weight values (Argonne National Laboratory, 2021; Islam et al., 2021) to scaleup the weights obtained via bottom-up calculations. This was needed as any comparative life-cycle evaluation of MHDVs across different propulsion technologies requires them to exhibit equivalent performance (such as on vehicle towing, for instance). Since Autonomie has already conducted this analysis and sized various component systems appropriately for this purpose (such as for engines, fuel-cell stacks, and transmission), these weights are combined with material composition (obtained using bottom-up approach) to determine the final MHDV material breakup. However, exceptions exist to this method for certain component systems within the *vehicle components* category and for other component categories (like *batteries* and *fluids*). These exceptions are discussed in the relevant subsections, with this subsection focusing solely on the *vehicle components* category.

For common component systems between this study and Autonomie (e.g., *transmission*; Table 3), the value of the system weight provided in Autonomie is used directly. However, when these systems have different definitions across both sources, a hybrid scale-up approach is used to combine system weights from Autonomie with weights obtained via bottom-up approach.

To better understand this scale-up, consider the example of chassis as defined in Autonomie with its definition in this study (Tables 3 and 7). In Autonomie, the chassis definition includes frame rails and cross-members, steer and drive axles, suspensions and brakes for these axles, driveshaft and inter-axle shaft, truck body, box/van/trailer, lift-gates, wheels, vehicle fluids, electronic accessory, and exhaust after-treatment. In contrast, this study incorporates frame rails and cross-members, axles, suspensions, brakes, driveshaft, inter-axle shaft, wheels, and tires in the definition of chassis, while accounting for truck body (includes electronic accessories), vehicle fluids, lift-gates, and exhaust after-treatment (in powertrain) as separate systems (Tables 3–13). Hence, the scaling-up approach for chassis is a three-step process to obtain the weight of individual component systems (Table 3) to reach Autonomie's vehicle weight (based on Equations 1–4, as explained below).

$$\begin{aligned} W_{Chassis,A\_def\_B} &= W_{cross\_members\_frame\_rails\_B} + W_{steer\_axle\_B} + W_{drive\_axle\_B} \\ &+ W_{suspensions\_B} + W_{truck\_body\_B} + W_{shafts\_B} + W_{vbt\_B} + W_{lift\_gate\_B} \\ &+ W_{after\_treatment\_B} \cdots\cdot \end{aligned} \quad (1)$$

$$WS\,(\%)_{component\_A\_def} = \frac{W_{component\_B}}{W_{Chassis,A\_def\_B}} \quad \cdots\cdot \quad (2)$$

$$W_{Chassis,A\_def} = W_{Overall\_chassis,A\_def} - \left(W_{vehicle\_fluids\_B} + W_{wheels\_B}\right) \quad \cdots\cdot \quad (3)$$

$$W_{component,A\_def} = WS\,(\%)_{component\_B} \times W_{Chassis,A\_def} \cdots\cdot \quad (4)$$

Consider any one of the chosen MHDVs (e.g., Class 6 ICEV MHDV). In the first step, the bottom-up weights of all individual components/constituent systems (excluding vehicle fluids and wheels) that constitute Autonomie's definition of the chassis (Table 3) are summed up (here, A_def is Autonomie-defined and B is bottom-up) to obtain the bottom-up weight of chassis as per Autonomie's definition (Equation 1). Wheels and vehicle fluids are excluded here as these elements cannot be reasonably scaled, as will be done with other components. Next, the bottom-up weight of all component systems is used to calculate their respective weight shares in the final bottom-up Autonomie-defined chassis weight (Equation 2). For instance, the weight share of truck body is obtained by dividing the bottom-up truck body weight ($W_{truck\_body\_B}$) by the summed bottom-up Autonomie-defined chassis weight ($W_{Chassis,A\_def\_B}$). Next, the combined bottom-up weight of wheels and vehicle fluids is subtracted from the overall Autonomie-supplied chassis weight (Equation 3). Subsequently, the weight shares obtained using Equation 2 are used to scale-up individual component systems, such that their final sum matches with the Autonomie-defined chassis weight (minus the vehicle fluids and wheels; Equation 4). A detailed description of the symbols used in Equations 1–4 is provided in Table 14.

Table 14 Description of symbols used in Equations 1–4

Symbols	Description
$W_{cross\_members\_frame\_rails\_B}$	Bottom-up weight of cross-members and frame rails
$W_{steer\_axle\_B}$	Bottom-up weight of steer axle
$W_{drive\_axle\_B}$	Bottom-up weight of drive axle
$W_{suspensions\_B}$	Bottom-up weight of suspensions and brakes for all axles
$W_{truck\_body\_B}$	Bottom-up weight of truck body
W_{shafts_B}	Bottom-up weight of driveshaft and inter-axle shaft
W_{vbt_B}	Bottom-up weight of van/box/trailer
$W_{lift\_gate\_B}$	Bottom-up weight of lift-gate system
$W_{after\_treatment\_B}$	Bottom-up weight of exhaust after-treatment system
$W_{Chassis,A\_def\_B}$	Bottom-up weight of chassis, where the chassis is defined as per Autonomie (Table 3)
$W_{component\_B}$	Bottom-up weight of component, where the component can be cross-members + frame rails, drive axle, steer axle, truck body, suspensions and brakes, driveshaft and inter-axle shaft, van/box/trailer, lift-gate, or exhaust after-treatment
$WS\ (\%)_{component\_B}$	Bottom-up weight share of component, where the component can be cross-members + frame rails, drive axle, steer axle, truck body, suspensions and brakes, driveshaft and inter-axle shaft, van/box/trailer, lift-gate, or exhaust after-treatment
$W_{vehicle\_fluids\_B}$	Bottom-up weight of vehicle fluids
W_{wheels_B}	Bottom-up weight of wheels
$W_{Overall\_chassis,A\_def}$	Overall weight of chassis in Autonomie
$W_{Chassis,A\_def}$	Weight of chassis (minus vehicle fluids and wheels) as per Autonomie, using the chassis definition from Autonomie
$W_{component,A\_def}$	Scaled-up weight of component to Autonomie truck weight, where the component can be cross-members + frame rails, drive axle, steer axle, truck body, suspensions and brakes, driveshaft and inter-axle shaft, van/box/trailer, lift-gate, or exhaust after-treatment

Apart from chassis, a simpler scale-up approach is used for the powertrain, transmission, and electric-drive components (traction motor and electronic controller, as generator is not used in any vehicle). For the powertrain, engine weight from the bottom-up approach is scaled up to the sum of engine, alternator/generator, and mechanical accessory weights in Autonomie for all ICEV and HEV MHDVs (Table 5). Similarly, the transmission weight from bottom-up approach is scaled up to the sum of the weight of transmission subsystem in Autonomie (clutch, gearbox, final drives, and truck coupling; Table 6). Lastly, like for the chassis, the sum of traction motor and electronic controller weights from the bottom-up approach is scaled up to the motor weight for EV MHDVs in Autonomie (Table 8), while maintaining a similar ratio of weight distribution between these two components as in the bottom-up approach (analogous to the three-step process used for chassis). Fuel tank weight is scaled up directly from Autonomie for this study. Conversely, like for wheels and vehicle fluids, the weight of tires obtained via the bottom-up approach is used directly in this study (within chassis) for the chosen MHDV, assuming it to be the same for MHDVs in both Autonomie and bottom-up versions.

Unlike the above-mentioned components, Autonomie is not used directly to determine the weight of batteries and fuel-cell parts (fuel-cell stacks as powertrain, and fuel-cell auxiliary systems or hydrogen tank storage systems; both are used in fuel-cell MHDVs). Instead, a mixture of alternative sources is used along with Autonomie-based parameters to determine the weight of these two components, while using their same definitions as used in Autonomie (see Tables 3–13). More information is provided in Sections 3.6 and 3.7.

3.5 Vehicle Components: Material Composition and Weight

Apart from weight, a fair comparison of MHDVs across various propulsion technologies requires detailed information on their material composition along with an appropriate sizing of their major constituent subsystems and individual parts. However, the literature review undertaken for this study did not identify any prior studies on dismantling and/or sizing subsystems/parts to estimate MHDV material composition, making it difficult to use this research to evaluate their life-cycle environmental output.

To overcome this, a bottom-up approach (discussed in Section 3.4) was used to collect the bottom-up weight and material composition data for MHDV component systems by compiling and aggregating the weight and composition of their individual parts and subsystems. A variety of data sources were used for this process, including: (a) technical literature (academic journals, conference papers, and academic and technical reports); (b) company literature (studies, websites, catalogs, etc.) from manufacturers and sellers of individual parts, subsystems, and/or component systems used in present-day versions of chosen MHDVs; (c) the existing GREET® model for LDVs (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006); (d) personal communication with Strategic Analysis (SA) regarding fuel-cell stacks and auxiliary components (fuel-cell onboard storage) (James et al., 2021); and (e) other assumptions, when necessary.

For component systems classified under the *vehicle components* category, the material composition of individual parts/subsystems were aggregated to derive the overall composition of each component system, and subsequently, for the entire truck for all MHDVs. The same approach was used for the *trailers* category as well, while the material composition of MHDV *vehicle fluids* was extended from the GREET® LDV model (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006). Appropriate modifications were made for the additional fluids that are used only in MHDVs.

Regarding *batteries*, the material composition of Pb-acid batteries was extended from the GREET® LDV model (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006). On the other hand, for Li-ion batteries, data was obtained via Battery Performance and Cost (BatPaC) 4.0 model by inputting MHDV-specific battery parameters (voltage, energy, current, and operating time) that are consistent with those used in the Autonomie model. Lastly, for fuel-cell components (fuel-cell stack and onboard storage), the material composition was obtained via suitable modification of details provided by SA (James et al., 2021). More information is given in Section 3.6.

A detailed list of data sources used to obtain material constituents and weights of individual parts and subsystems for each component system is provided in Table 15. In addition, for each system, the weight share of various subsystems is calculated and used for subsequent analysis.

Apart from material composition, a few critical assumptions are made in this study to conduct like-for-like comparison of MHDVs spanning various propulsion technologies. The material composition and weight of truck body and chassis are assumed to be the same across all propulsion technologies for a single MHDV (be it Class 6 PnD, Class 8 day-cab, or Class 8 sleeper-cab truck). On similar lines, the material composition and weight of van/box (for Class 6 trucks) and trailer (for Class 8 trucks) are also considered to be the same, regardless of the propulsion technology used. However, these assumptions cannot be extended to other components for all the MHDVs due to variation in their incorporation and sizing with changes in propulsion technology (ICEV, HEV, EV, or FCV). Another key assumption is for trailers, whose operational lifetime is treated to be the same as that of Class 8 truck tractor. Other key assumptions for various component systems and/or their subsystems are provided in Table 16.

Table 15 Data sources for MHDV component systems: Weight and material composition

Component Systems	Sub-components	Key References
Truck Body	Interior and Exterior Parts	(75 Chrome Shop, 2021; Auto Zone Inc., 2021; Big Rig World, 2021; Big Truck Hoods, 2021; Cardone, 2019; Daimler Trucks North America LLC, 2021; Fleet Truck Parts, 2021; Pradeep et al., 2017; Ragatz & Thornton, 2016; Truck iD, 2021)
Chassis	Cross-members and Frame Rails	(Big Rig World, 2021; Navistar Inc., 2021; RitchieSpecs, 2018; Volvo Group, 2021)
	Axles, Suspension, and Brakes	(Dana Ltd., 2021; Dana Ltd. & Dana Spicer, 2021; Dana Spicer, 2019; FinditParts Inc., 2021; SAF-Holland Group, 2021; W. W. Grainger Inc., 2021)
	Wheels and Tires	(Buy Truck Wheels, 2021; The Goodyear Tire & Rubber Company, 2021)
	Fifth-wheel	(FinditParts Inc., 2021; SAF-Holland Group, 2021)
	Differential and Electrical System	(Dana Ltd., 2021; Dana Ltd. & Dana Spicer, 2021; Dana Spicer, 2019)
Powertrain	Engines	(Cummins, 2021)
	Fuel Cell Stacks	(James et al., 2021)
	Others	(4 State Trucks, 2021)
Transmission		(Drivetrain America, 2021; Eaton, 2014; W. W. Grainger Inc., 2021)
Electric-drive Components	Traction Motor	(Dana Ltd. & Dana Spicer, 2021; Dana Spicer, 2019)
	Generator	
	Electronic Controller	
Fuel cell Auxiliary Components	Hydrogen Tanks	(Argonne National Laboratory, 2021; Islam et al., 2021; James et al., 2021)

Table 15 (Cont.)

Component Systems	Sub-components	Key References
Van/Box/Trailer		(Chassis King, 2021; FinditParts Inc., 2021; Morgan Truck Body, 2021; SAF-Holland Group, 2021; STI Holdings Inc., 2012, 2021; W. W. Grainger Inc., 2021)
Batteries		(Argonne National Laboratory, 2018, 2021; Interstate Batteries, 2021; Islam et al., 2021)
Fluids		(Auto Zone Inc., 2021; Cummins, 2021; Cummins Filtration, 2021; Dana Ltd., 2021; Dana Ltd. & Dana Spicer, 2021; Dana Spicer, 2019; Eaton, 2018)
Lift-gates		(Woodbine Manufacturing Company Inc., 2018)

Table 16 Key assumptions for MHDVs

Aspects	Assumptions and Underlying Reason

Material Inventory	• No inventory (energy use and emissions) considered for nichrome and bronze, with their material composition assumed using literature:
	  - Nichrome: 80% nickel + 20% chromium
	  - Bronze: 88% copper + 12% tin
	• No inventory (material use, energy use, and emissions) considered for damask fiber, leather, latex, cotton paper, ceramic, wood, tin, niobium, chromium, and titanium
	• Inventory for brass considered to be the same as that for copper
	• Inventory for magnet considered to be the same as that for iron
	• Inventory for silica considered to be the same as that for sand
	• Underlying reason: Lack of alternative data/inventory in current GREET® model and literature

Material Composition/Use	• Amount of virgin and recycled share for different materials assumed to be the same as that for LDVs in GREET® • Material composition of average plastic for MHDVs assumed to be the same as that for LDVs in GREET® • Underlying reason: Lack of alternative data/inventory in literature
Component Systems	• Material composition of engine (including engine unit, powertrain thermal and electrical systems, and emission control electronics) assumed to be the same for both ICEV and HEV powertrains for any one type of MHDV (Class 6 PnD or Class 8 day-cab/sleeper-cab) • Material composition of transmission systems assumed to be the same for all powertrains for any one type of MHDV • Material composition of electric drive components (traction motor, electronic controller, and generator) assumed to be the same as that for these components in GREET® LDVs • Lift-gates assumed to be made entirely of steel due to lack of material composition break-up in literature

Tables 17–19 provide the weight of all component systems (excluding *batteries* and *fluids*) and their major subsystems for the chosen MHDVs. While system weights are based on the scaled-up hybrid approach, subsystem weights are the product of their respective weight shares within the system (obtained via bottom-up approach) and the overall system weight (obtained from Autonomie or using Autonomie). Tables 20–22 provide the weight share of each component system, developed by calculating their respective weight by the sum of weight of all systems (i.e., the entire MHDV minus the combined weight of batteries, fluids, and fuel). Material composition of all constituent systems, and of the MHDV (as obtained via bottom-up approach), are provided in Tables 23–28.

Table 17 Weights for component systems, their important subsystems, and overall MHDV: Class 6 PnD truck (lbs.)

Component System/Subsystem	ICEV	HEV	EV	FCV
Truck Body				
Body and Glass	1,117	1,117	1,117	1,117
Interior	1,002	1,002	1,002	1,002
Exterior	288	288	288	288
Chassis				
Steer Axle (includes brakes)	759	759	759	759
Drive Axle (includes brakes and differential assembly)	958	958	958	958
Shafts (driveshaft, axle, and inter-axle shaft)	113	113	113	113
Suspensions (steer and drive axles)	1,104	1,104	1,104	1,104
Wheels and Tires	1,020	1,020	1,020	1,020
Cradle (frame rails, cross-members), Fifth-wheel, and Auxiliary	2,207	2,207	2,207	2,207
Powertrain				
Engine Unit (inclusive of powertrain thermal and electrical system, and emission control electronics)	992	895	0	0
Fuel-cell Stack	0	0	0	558
Engine Fuel Storage + Exhaust Systems	430	430	0	0
Transmission				
Clutch	55	55	0	0
Gearbox	366	364	154	154
Final Drive and Coupling	66	66	44	55
Electric-drive Components				
Traction Motor	0	105	295	295
Generator	0	0	0	0
Electronic Controller	0	10	29	29
Fuel-cell Onboard Storage	0	0	0	489
Van-box	4,772	4,772	4,772	4,772
Lift-gates	1,325	1,325	1,325	1,325

Table 18 Weights for component systems, their important subsystems, and overall MHDV: Class 8 day-cab truck (lbs.)

Component System/Subsystem	ICEV	HEV	EV	FCV
Truck Body				
Body and Glass	1,258	1,258	1,258	1,258
Interior	1,281	1,281	1,281	1,281
Exterior	214	214	214	214
Chassis				
Steer Axle (includes brakes)	759	759	759	759
Drive Axle (includes brakes and differential assembly)	958	958	958	958
Shafts (driveshaft, axle, and inter-axle shaft)	113	113	113	113
Suspensions (steer and drive axles)	1,104	1,104	1,104	1,104
Wheels and Tires	1,020	1,020	1,020	1,020
Cradle (frame rails, cross-members), Fifth-wheel, and Auxiliary	2,207	2,207	2,207	2,207
Powertrain				
Engine Unit (inclusive of powertrain thermal and electrical system, and emission control electronics)	2,610	2,582	0	0
Fuel-cell Stack	0	0	0	1,532
Engine Fuel Storage + Exhaust Systems	398	398	0	0
Transmission				
Clutch	55	55	0	0
Gearbox	778	778	315	324
Final Drive and Coupling	110	110	88	88
Electric-drive Components				
Traction Motor	0	183	626	642
Generator	0	0	0	0
Electronic Controller	0	19	66	68
Fuel-cell Onboard Storage	0	0	0	2,209
Trailer				
Trailer Body	5,558	5,558	5,558	5,558
Trailer Chassis	4,423	4,423	4,423	4,423
Trailer Auxiliary	594	594	594	594

Table 19 Weights for component systems, their important subsystems, and overall MHDV: Class 8 sleeper-cab truck (lbs.)

Component System/Subsystem	ICEV	HEV	EV	FCV
Truck Body				
Body and Glass	1,444	1,444	1,444	1,444
Interior	1,559	1,559	1,559	1,559
Exterior	343	343	343	343
Chassis				
Steer Axle (includes brakes)	759	759	759	759
Drive Axle (includes brakes and differential assembly)	958	958	958	958
Shafts (driveshaft, axle, and inter-axle shaft)	113	113	113	113
Suspensions (steer and drive axles)	1,104	1,104	1,104	1,104
Wheels and Tires	1,020	1,020	1,020	1,020
Cradle (frame rails, cross-members), Fifth-wheel, and Auxiliary	2,207	2,207	2,207	2,207
Powertrain				
Engine Unit (inclusive of powertrain thermal and electrical system, and emission control electronics)	2,610	2,582	0	0
Fuel-cell Stack	0	0	0	1,525
Engine Fuel Storage + Exhaust Systems	411	411	0	0
Transmission				
Clutch	55	55	0	0
Gearbox	778	778	315	322
Final Drive and Coupling	110	110	88	88
Electric-drive Components				
Traction Motor	0	183	624	638
Generator	0	0	0	0
Electronic Controller	0	19	66	68
Fuel-cell Onboard Storage	0	0	0	4,609
Trailer				
Trailer Body	5,974	5,974	5,974	5,974
Trailer Chassis	4,652	4,652	4,652	4,652
Trailer Auxiliary	638	638	638	638

Table 20 Weight breakdown of Class 6 PnD trucks (%)

Component System	ICEV	HEV	EV	FCV
Truck Body	14.5	14.5	15.9	14.8
Powertrain	8.6	8.0	0.0	3.4
Transmission	2.9	2.9	1.3	1.3
Chassis	37.2	37.1	40.6	37.9
Traction Motor	0.0	0.6	1.9	1.8
Generator	0.0	0.0	0.0	0.0
Electronic Controller	0.0	0.1	0.2	0.2
Fuel-cell Onboard Storage	0.0	0.0	0.0	3.0
Van/Box	28.8	28.8	31.4	29.4
Lift-gates	8.0	8.0	8.7	8.2

Table 21 Weight breakdown of Class 8 day-cab trucks (%)

Component System	ICEV	HEV	EV	FCV
Truck Body	10.4	10.3	11.6	10.0
Powertrain	11.3	11.2	0.0	5.6
Transmission	3.6	3.5	1.7	1.5
Chassis	34.9	34.7	39.1	33.8
Traction Motor	0.0	0.7	2.6	2.3
Generator	0.0	0.0	0.0	0.0
Controller or Inverter	0.0	0.1	0.3	0.2
Fuel-cell Auxiliary Components	0.0	0.0	0.0	8.0
Trailer	39.8	39.6	44.6	38.5

Table 22 Weight breakdown of Class 8 sleeper-cab trucks (%)

Component System	ICEV	HEV	EV	FCV
Truck Body	11.6	11.6	12.9	10.4
Powertrain	10.5	10.3	0.0	4.8
Transmission	3.3	3.3	1.6	1.3
Chassis	35.4	35.2	39.3	31.8
Traction Motor	0.0	0.6	2.4	2.0
Generator	0.0	0.0	0.0	0.0
Controller or Inverter	0.0	0.1	0.3	0.2
Fuel-cell Auxiliary Components	0.0	0.0	0.0	14.4
Van/Box/Trailer	39.2	38.9	43.5	35.2

Table 23 Material composition of component systems and subsystems in Class 6 PnD trucks

Component System/Subsystem	Material Composition
Body (all powertrains)	
Body and Glass	38% glass fiber-reinforced plastic 22% steel 20% glass 16% wrought aluminum 4% plastic (average)
Interior	61% steel 21% plastic (average) 8% cast aluminum 5% rubber 3% leather 1% wrought aluminum ~1% others (copper/brass, damask, latex, and cotton paper)
Exterior and Auxiliary	38% plastic 30% steel 10% rubber 9% cast aluminum 8% glass 5% copper/brass ~0% wrought aluminum
Chassis (all powertrains)	
Tires (steer and drive)	66.7% rubber 33% steel
Wheels (steer and drive)	100% aluminum
Steer Axle (including brakes)	61% steel 39% cast iron ~0% others (cast and wrought aluminum, rubber, plastic, brass, copper, and magnet)
Drive Axle (including brakes and differential assembly)	76% steel 23% cast iron ~1% others (cast aluminum, rubber, plastic, brass, and magnet)

Table 23 (Cont.)

Component System/Subsystem	Material Composition
Chassis (all powertrains)	
Tires (steer and drive)	66.7% rubber 33% steel
Wheels (steer and drive)	100% aluminum
Steer Axle (including brakes)	61% steel 39% cast iron ~0% others (cast and wrought aluminum, rubber, plastic, brass, copper, and magnet)
Drive Axle (including brakes and differential assembly)	76% steel 23% cast iron ~1% others (cast aluminum, rubber, plastic, brass, and magnet)
Suspensions (drive and steer axles)	91% steel 3% cast iron 6% rubber ~0% plastic
Shafts (driveshaft, inter-axle shaft, axle shaft)	95% steel 5% cast iron ~0% others (rubber, plastic, and grease)
Cradle, Fifth-wheel, and Auxiliary	100% steel
Powertrain	
Engine Unit (inclusive of powertrain thermal and electrical system, and emission control electronics; ICEV and HEV powertrains)	53% cast iron 37% steel 6% cast aluminum 2% wrought aluminum 1% plastic ~1% others (stainless steel, rubber, nichrome, and others)

Table 23 (Cont.)

Component System/Subsystem	Material Composition
Powertrain	
Fuel-cell Stack (FCV powertrain)	40% stainless steel 12% polypropylene (PP) 11% steel 8% wrought aluminum 7% cast aluminum 4% average plastic 3% each of glass fiber-reinforced plastic, rubber, polyethylene terephthalate (PET), and copper/brass 2% plastic [polyphenylene sulfide (PPS) and other plastics] 1.5% carbon 1% each of carbon paper and perfluoro sulfonic acid (PFSA) 0% others [polytetrafluoroethylene (PTFE), nickel, iron, nylon, chromium, platinum, high-density polyethylene (HDPE), molybdenum, glass, ceramic, niobium, titanium, cast iron, bronze, graphite, fiberglass, nichrome, PFSA Nafion, and others]
Engine Fuel Storage + Exhaust Systems (ICEV and HEV powertrains)	33% wrought aluminum 24% ceramic 19% plastic (average) 14% stainless steel 10% steel ~0% others (rubber and platinum)
Transmission (all powertrains)	69% steel 24% cast iron 6% cast aluminum ~1% others (wrought aluminum, rubber, plastic, copper, brass, magnet, and grease)
Electric-drive components (HEV, EV, and FCV powertrains)	
Traction Motor and Generator	36% steel 36% cast aluminum 28% copper and brass

Table 23 (Cont.)

Component System/Subsystem	Material Composition
Electric-drive Components (HEV, EV, and FCV powertrains)	
Electronic Controller	5% steel 47% cast aluminum 8% copper and brass 4% rubber 24% average plastic 12% others
Fuel-cell Onboard Storage	73% carbon fiber-reinforced composite 13% stainless steel 6% wrought aluminum 3% each of HDPE and steel 2% PP ~0% others
Van-box (all powertrains)	46% wrought aluminum 41% wood 11% steel 1% rubber ~1% others (cast aluminum, stainless steel, plastic, copper, brass)
Lift-gates	100% steel

Table 24 Material composition of component systems and subsystems in Class 8 day-cab trucks

Component System/Subsystem	Material Composition
Body (all powertrains)	
Body and Glass	38% glass fiber-reinforced plastic 25% wrought aluminum 19% glass 15% steel 4% plastic (average)
Interior	58% steel 33% plastic (average) 5% cast aluminum 3% rubber 1% wrought aluminum ~0% others (copper/brass, damask, latex, cotton paper, and leather)
Exterior and Auxiliary	35% plastic 34% steel 12% rubber 7% glass 6% cast aluminum 6% copper/brass ~0% wrought aluminum
Chassis (all powertrains)	
Steer Axle (including brakes)	62% steel 37% cast iron ~1% others (cast and wrought aluminum, rubber, plastic, brass, copper, and magnet)
Drive Axle (including brakes and differential assembly)	82% steel 17% cast iron ~1% others (cast aluminum, rubber, plastic, brass, and magnet)

Table 24 (Cont.)

Component System/Subsystem	Material Composition
Chassis (all powertrains)	
Suspensions (drive and steer axles)	92% steel 6% rubber 2% cast iron ~0% plastic
Shafts (driveshaft, inter-axle shaft, and axle shaft)	96% steel 4% cast iron ~0% others (rubber, plastic, and grease)
Wheels (steer and drive)	100% aluminum
Tires (steer and drive)	66.7% rubber 33% steel
Cradle, Fifth-wheel, and Auxiliary	100% steel
Powertrain	
Engine Unit (inclusive of powertrain thermal and electrical system, and emission control electronics; ICEV and HEV powertrains)	46% steel 37% cast iron 8% cast aluminum 3% wrought aluminum 3% plastic 1% each, rubber, and copper ~1% others (stainless steel, iron, nichrome, and others)

Table 24 (Cont.)

Component System/Subsystem	Material Composition
Powertrain	
Fuel-cell Stack (FCV powertrain)	52% stainless steel 10% PP 7% cast aluminum 6% each of steel and wrought aluminum 4% glass fiber-reinforced plastic 3% PET 2% plastic (polyphenylene sulfide and other plastics) 2% each of average plastic, copper/brass, and carbon 1% each of carbon paper, rubber, and PFSA 0% others (PTFE, nickel, iron, nylon, chromium, platinum, HDPE, molybdenum, glass, ceramic, niobium, titanium, cast iron, bronze, graphite, fiberglass, nichrome, PFSA Nafion, and others)
Engine Fuel Storage + Exhaust Systems (ICEV and HEV powertrains)	44% wrought aluminum 23% ceramic 16% plastic (average) 13% stainless steel 4% steel ~0% others (rubber and platinum)
Transmission (all powertrains)	86% steel 7% cast iron 5% plastic ~2% others (cast and wrought aluminum, rubber, plastic, copper, brass, magnet, and grease)
Electric-drive Components (HEV, EV, and FCV powertrains)	
Traction Motor and Generator	36% steel 36% cast aluminum 28% copper and brass

Table 24 (Cont.)

Component System/Subsystem	Material Composition
Electric-drive Components (HEV, EV, and FCV powertrains)	
Electronic Controller	5% steel 47% cast aluminum 8% copper and brass 4% rubber 24% average plastic 12% others
Fuel-cell Onboard Storage (FCV powertrain)	64% carbon fiber-reinforced composite 29% stainless steel 3% wrought aluminum 2% each of HDPE and PP 1% steel ~0% others
Trailer (all powertrains)	
Trailer Body	51% wrought aluminum 38% wood 11% steel ~0% others (cast aluminum and rubber)
Trailer Chassis	57% steel 19% rubber 13% cast iron 9% cast aluminum 2% ceramic ~0% others (stainless steel, wrought aluminum, plastic, grease, and magnets)
Trailer Auxiliary	69% steel 17% glass fiber-reinforced plastic 6% wrought aluminum 5% rubber ~3% others (stainless steel, plastic, copper, brass, and others)

Table 25 Material composition of component systems/subsystems in Class 8 sleeper-cab trucks

Component System/Subsystem	Material Composition
Body (all powertrains)	
Body and Glass	36% glass fiber-reinforced plastic 23% wrought aluminum 19% steel 18% glass 3% plastic (average)
Interior	49% steel 25% plastic (average) 7% damask 5% each of latex and cast aluminum 4% leather 3% rubber 1% wrought aluminum ~0% others (copper/brass and cotton paper)
Exterior and Auxiliary	43% plastic 24% steel 10% each of cast aluminum and glass 8% rubber 4% copper/brass ~0% wrought aluminum
Chassis (all powertrains)	
Wheels (steer and drive)	100% aluminum
Tires (steer and drive)	66.7% rubber 33% steel
Steer Axle (including brakes)	62% steel 37% cast iron ~1% others (cast and wrought aluminum, rubber, plastic, brass, copper, and magnet)
Drive Axle (including brakes and differential assembly)	82% steel 17% cast iron ~1% others (cast aluminum, rubber, plastic, brass, and magnet)

Table 25 (Cont.)

Component System/Subsystem	Material Composition
Chassis (all powertrains)	
Suspensions (drive and steer axles)	92% steel 2% cast iron 6% rubber ~0% plastic
Shafts (driveshaft, inter-axle shaft, and axle shaft)	96% steel 4% cast iron ~0% others (rubber, plastic, and grease)
Cradle, Fifth-wheel, and Auxiliary	98% steel 2% rubber
Powertrain	
Engine Unit (inclusive of powertrain thermal and electrical system, and emission control electronics; ICEV and HEV powertrains)	46% steel 37% cast iron 8% cast aluminum 3% wrought aluminum 3% plastic ~3% (rubber, copper, stainless steel, iron, nichrome, and others)
Fuel-cell Stack (FCV powertrain)	52% stainless steel 10% PP 7% cast aluminum 6% each of steel and wrought aluminum 4% glass fiber-reinforced plastic 3% PET 2% plastic (polyphenylene sulfide and other plastics) 2% each of average plastic, copper/brass, and carbon 1% each of carbon paper, rubber, and PFSA 0% others (PTFE, nickel, iron, nylon, chromium, platinum, HDPE, molybdenum, glass, ceramic, niobium, titanium, cast iron, bronze, graphite, fiberglass, nichrome, PFSA Nafion, and others)

Table 25 (Cont.)

Component System/Subsystem	Material Composition
Powertrain	
Engine Fuel Storage + Exhaust Systems (ICEV and HEV powertrains)	35% wrought aluminum 23% ceramic 19% plastic (average) 13% stainless steel 10% steel ~0% others (rubber and platinum)
Transmission (all powertrains)	86% steel 7% cast iron 5% plastic 1% rubber ~1% others (cast aluminum, wrought aluminum, rubber, plastic, copper, brass, magnet, and grease)
Electric-drive Components (HEV, EV, and FCV powertrains)	
Traction Motor and Generator	36% steel 36% cast aluminum 28% copper and brass
Electronic Controller	5% steel 47% cast aluminum 8% copper and brass 4% rubber 24% average plastic 12% others
Fuel-cell Onboard Storage (FCV powertrain)	55% carbon fiber-reinforced composite 39% stainless steel 2% each of wrought aluminum and HDPE 1% each of steel and PP ~0% others

Table 25 (Cont.)

Component System/Subsystem	Material Composition
Trailer (all powertrains)	
Trailer Body	51% wrought aluminum 38% wood 11% steel ~0% others (cast aluminum and rubber)
Trailer Chassis	58% steel 18% rubber 14% cast iron 9% cast aluminum ~1% others (ceramic, stainless steel, wrought aluminum, plastic, grease, and magnets)
Trailer Auxiliary	69% steel 17% glass fiber-reinforced plastic 6% wrought aluminum 5% rubber ~3% others (stainless steel, plastic, copper, brass, and others)

Table 26 Material composition of Class 6 PnD trucks (aggregated over all component systems; wt.%)

Materials	ICEV	HEV	EV	FCV
Steel	49.4	49.4	50.6	47.8
Stainless Steel	0.9	0.9	0.6	2.3
Cast Iron	7.2	6.9	4.0	3.7
Cast Aluminum	3.1	3.4	3.7	3.7
Wrought Aluminum	15.5	15.4	15.8	15.2
Copper and Brass	0.1	0.3	0.7	0.8
Magnet	0.0	0.0	0.0	0.0
Bronze	0.0	0.0	0.0	0.0
Iron	0.0	0.0	0.0	0.0
Nichrome	0.0	0.0	0.0	0.0
Nickel	0.0	0.0	0.0	0.0
Chromium	0.0	0.0	0.0	0.0
Molybdenum	0.0	0.0	0.0	0.0
Niobium	0.0	0.0	0.0	0.0
Titanium	0.0	0.0	0.0	0.0
Platinum	0.0	0.0	0.0	0.0
Rubber	4.1	4.1	4.5	4.3
Plastic (average)	2.9	2.9	2.6	2.6
Nylon	0.0	0.0	0.0	0.0
PP	0.0	0.0	0.0	0.5
HDPE	0.0	0.0	0.0	0.1
PET	0.0	0.0	0.0	0.1
PTFE	0.0	0.0	0.0	0.0
PFSA	0.0	0.0	0.0	0.0
Plastic (PPS and others)	0.0	0.0	0.0	0.1
PFSA Nafion	0.0	0.0	0.0	0.0
Carbon Fiber-reinforced Plastic	0.0	0.0	0.0	2.2
Glass Fiber-reinforced Plastic	2.6	2.6	2.8	2.7
Fiberglass	0.0	0.0	0.0	0.0
Glass	1.5	1.5	1.6	1.5
Graphite	0.0	0.0	0.0	0.0
Ceramic	0.6	0.6	0.0	0.0
Carbon	0.0	0.0	0.0	0.1
Cotton Paper	0.0	0.0	0.0	0.0
Grease	0.0	0.0	0.0	0.0
Damask	0.0	0.0	0.0	0.0
Latex	0.0	0.0	0.0	0.0
Leather	0.2	0.2	0.2	0.2
Silica	0.0	0.0	0.0	0.0
Carbon Paper	0.0	0.0	0.0	0.0
Wood	11.7	11.7	12.8	12.0
Others	0.0	0.0	0.0	0.0

Table 27 Material composition of Class 8 day-cab trucks (aggregated over all component systems; wt.%)

Materials	ICEV	HEV	EV	FCV
Steel	50.8	50.7	50.7	44.2
Stainless Steel	0.6	0.5	0.4	5.6
Cast Iron	8.8	8.7	5.6	4.9
Cast Aluminum	4.6	4.9	5.4	5.1
Wrought Aluminum	13.2	13.1	13.7	12.4
Copper and Brass	0.2	0.4	0.9	0.9
Magnet	0.0	0.0	0.0	0.0
Bronze	0.0	0.0	0.0	0.0
Iron	0.0	0.0	0.0	0.0
Nichrome	0.0	0.0	0.0	0.0
Nickel	0.0	0.0	0.0	0.0
Chromium	0.0	0.0	0.0	0.0
Molybdenum	0.0	0.0	0.0	0.0
Niobium	0.0	0.0	0.0	0.0
Titanium	0.0	0.0	0.0	0.0
Platinum	0.0	0.0	0.0	0.0
Rubber	7.3	7.2	8.0	7.0
Plastic (average)	2.1	2.1	1.7	1.6
Nylon	0.0	0.0	0.0	0.0
PP	0.0	0.0	0.0	0.7
HDPE	0.0	0.0	0.0	0.2
PET	0.0	0.0	0.0	0.2
PTFE	0.0	0.0	0.0	0.0
PFSA	0.0	0.0	0.0	0.0
Plastic (PPS and others)	0.0	0.0	0.0	0.1
PFSA Nafion	0.0	0.0	0.0	0.0
Carbon Fiber-reinforced Plastic	0.0	0.0	0.0	5.1
Glass Fiber-reinforced Plastic	2.6	2.6	2.9	2.7
Fiberglass	0.0	0.0	0.0	0.0
Glass	1.2	1.1	1.3	1.1
Graphite	0.0	0.0	0.0	0.0
Ceramic	0.6	0.6	0.3	0.3
Carbon	0.0	0.0	0.0	0.1
Cotton Paper	0.0	0.0	0.0	0.0
Grease	0.0	0.0	0.0	0.0
Damask	0.0	0.0	0.0	0.0
Latex	0.0	0.0	0.0	0.0
Leather	0.0	0.0	0.0	0.0
Silica	0.0	0.0	0.0	0.0
Carbon Paper	0.0	0.0	0.0	0.1
Wood	8.0	8.0	9.0	7.7
Others	0.0	0.0	0.0	0.0

Table 28 Material composition of Class 8 sleeper-cab trucks (aggregated over all component systems; wt.%)

Materials	ICEV	HEV	EV	FCV
Steel	51.5	51.4	51.5	42.0
Stainless Steel	0.5	0.5	0.3	8.4
Cast Iron	8.5	8.4	5.5	4.5
Cast Aluminum	4.3	4.6	5.0	4.4
Wrought Aluminum	12.7	12.6	13.2	11.3
Copper and Brass	0.2	0.3	0.8	0.7
Magnet	0.0	0.0	0.0	0.0
Bronze	0.0	0.0	0.0	0.0
Iron	0.0	0.0	0.0	0.0
Nichrome	0.0	0.0	0.0	0.0
Nickel	0.0	0.0	0.0	0.0
Chromium	0.0	0.0	0.0	0.0
Molybdenum	0.0	0.0	0.0	0.0
Niobium	0.0	0.0	0.0	0.0
Titanium	0.0	0.0	0.0	0.0
Platinum	0.0	0.0	0.0	0.0
Rubber	6.8	6.8	7.5	6.1
Plastic (average)	2.9	2.9	2.5	2.2
Nylon	0.0	0.0	0.0	0.0
PP	0.0	0.0	0.0	0.7
HDPE	0.0	0.0	0.0	0.2
PET	0.0	0.0	0.0	0.1
PTFE	0.0	0.0	0.0	0.0
PFSA	0.0	0.0	0.0	0.0
Plastic (PPS and others)	0.0	0.0	0.0	0.1
PFSA Nafion	0.0	0.0	0.0	0.0
Carbon Fiber-reinforced Plastic	0.0	0.0	0.0	7.8
Glass Fiber-reinforced Plastic	2.2	2.1	2.4	2.1
Fiberglass	0.0	0.0	0.0	0.0
Glass	1.0	1.0	1.2	0.9
Graphite	0.0	0.0	0.0	0.0
Ceramic	0.6	0.6	0.3	0.2
Carbon	0.0	0.0	0.0	0.1
Cotton Paper	0.0	0.0	0.0	0.0
Grease	0.0	0.0	0.0	0.0
Damask	0.4	0.4	0.4	0.3
Latex	0.3	0.3	0.3	0.3
Leather	0.2	0.2	0.2	0.2
Silica	0.0	0.0	0.0	0.0
Carbon Paper	0.0	0.0	0.0	0.1
Wood	8.0	7.9	8.8	7.1
Others	0.0	0.0	0.0	0.0

3.6 Fuel-cell Components and Batteries: Sizing, Weight, and Material Composition

Fuel-cell stack net power values, based on Autonomie results (Argonne National Laboratory, 2021), are provided in Table 29. Since these power values are different from those obtained from SA (James et al., 2021), the weight-to-power ratio for SA's fuel-cell stack is used to obtain the weight of the fuel-cell stack to coincide with the power requirement as defined by Autonomie. The weight-to-power ratio for each MHDV is used to calculate the total weight and weight break-up (by individual parts) for fuel-cell stack systems for MHDVs, with the total weight values given in Table 30.

Table 29 Net fuel-cell stack power values (in kW) for different vehicles for both Autonomie and SA

Type of MHDV	Net Fuel-cell Stack Power Values (kW)	
	Autonomie	SA
Class 6 PnD	195	160
Class 8 Day-cab	428	275
Class 8 Sleeper-cab	426	275

Table 30 Total weight of fuel-cell stack system (lbs.) for MHDVs for both Autonomie and SA

Type of MHDV	Weight of Fuel-cell Stack System (lbs.)	
	Autonomie	SA
Class 6 PnD	558	476
Class 8 Day-cab	1,532	1,021
Class 8 Sleeper-cab	1,525	1,021

On the other hand, for fuel-cell onboard storage (or hydrogen tank storage systems), calculations made by SA are used to obtain their final weight and break-up (by constituent components) after modifying: (a) the total weight of hydrogen stored (in line with the amount given by Autonomie); and (b) the number of tanks for all fuel-cell MHDVs (assuming the maximum storage of 10 kg of hydrogen per tank). Two scenarios are considered regarding the pressure of hydrogen stored in these tanks: 700-bar (the default scenario, for which data/weight values are used in Tables 17–28) and 350-bar.

Table 31 shows the overall weight and material composition of fuel-cell onboard storage (hydrogen tanks + other balance of plant) for both pressure scenarios for all MHDVs, while Table 32 shows the number of hydrogen tanks and total amount of hydrogen stored in these vehicles for both these pressure scenarios.

Table 31 Material composition and weight of 700-bar and 350-bar fuel-cell onboard storage systems for all MHDVs

Materials	Class 6 PnD: Weight Share (wt.%)		Class 8 Day-cab: Weight Share (wt.%)		Class 8 Sleeper-cab: Weight Share (wt.%)	
	700-bar	350-bar	700-bar	350-bar	700-bar	350-bar
Carbon Fiber-reinforced Plastic	73.4	53.0	63.5	35.8	54.5	28.3
Steel	2.8	1.2	1.2	0.6	0.8	0.4
Stainless Steel	13.2	29.6	28.6	53.3	39.3	63.2
Glass Fiber-reinforced Plastic	0.0	0.0	0.0	0.0	0.0	0.0
Wrought Aluminum	6.1	7.3	3.2	4.4	2.4	3.4
Copper	0.0	0.0	0.0	0.0	0.0	0.0
PP	1.8	4.0	1.5	2.7	1.3	2.1
HDPE	2.7	4.9	2.0	3.2	1.7	2.6
Others	0.0	0.0	0.0	0.0	0.0	0.0

Table 32 Number of hydrogen tanks and overall hydrogen amount stored in MHDVs as per SA

Type of MHDV	Amount of Hydrogen Stored (kg)	Number of Tanks Used	
		700-bar	350-bar
Class 6 PnD	11	2	3
Class 8 Day-cab	43	5	8
Class 8 Sleeper-cab	77	8	12

Since the fuel-cell stack power values are typically in line with battery power requirements for hybrid FCVs, battery power values for Li-ion batteries are also chosen from Autonomie (Argonne National Laboratory, 2021), which are provided in Table 33. Similar to fuel-cell stack sizing, HEV Li-ion batteries are sized by power, with their power values also taken from Autonomie (Table 33). Conversely, unlike for HEVs and FCVs, EV Li-ion batteries are sized by energy. These energy values, taken from Autonomie, are shown in Table 34. These power values (for HEVs and FCVs) and energy values (for EVs) are inputted in the BatPaC 4.0 model (Argonne National Laboratory, 2018) to determine the total weight of Li-ion batteries for HEV, EV, and FCV MHDVs. BatPaC was used because it computes bottom-up weight and material composition estimates of Li-ion batteries based on specific battery parameters (battery energy/power requirement as provided in Autonomie, and other parameters, such as number of cells/module, number of modules/battery, and current). For MHDVs, we modeled four cathode options for HEV and FCV MHDVs and three options for EV MHDVs, all based on the NMC (nickel-manganese-cobalt) chemistry (NMC811, NMC622, NMC532, and NMC111, with the last used only in HEV and FCV MHDVs). Specific power and energy values of these options, as obtained via BatPaC 4.0 model, are provided in Table 35. Along with these values, material composition and overall weight of Li-ion batteries (all NMC options) across all these powertrains are provided in Tables 36–44.

Table 33 Battery power values (in kW) for HEV and FCV MHDVs, taken from Autonomie

Type of MHDV	Power Values (kW) for Li-ion Batteries	
	HEV	FCV
Class 6 PnD	157	190
Class 8 Day-cab	219	112
Class 8 Sleeper-cab	219	112

Table 34 Battery energy values (in kWh) for EV MHDVs, taken from Autonomie

Type of MHDV	Energy Requirement for EV MHDVs (kWh) from Li-ion Batteries
Class 6 PnD	261
Class 8 Day-cab	909
Class 8 Sleeper-cab	1,622

Table 35 Specific power and energy values of Li-ion batteries for different MHDVs

Type of MHDV	Li-ion Battery Chemistry	Specific Power (W/kg)		Specific Energy (Wh/kg)
		HEV	FCV	EV
Class 6 PnD	NMC811	2,760	2,969	162
	NMC622	2,650	2,844	154
	NMC532	2,546	2,740	146
	NMC111	2,519	2,697	N/A
Class 8 Day-cab	NMC811	3,112	1,215	207
	NMC622	2,808	1,164	196
	NMC532	2,694	1,112	183
	NMC111	2,652	1,094	N/A
Class 8 Sleeper-cab	NMC811	3,112	1,271	223
	NMC622	2,808	1,214	210
	NMC532	2,694	1,166	196
	NMC111	2,652	1,147	N/A
N/A = Not applicable				

Table 36 Material composition of Li-ion batteries in Class 6 PnD trucks (HEV) (%)

Materials	Material Composition (wt.%)			
	NMC811	NMC622	NMC532	NMC111
Cathode (active material)	11.1	12.5	13.8	14.1
Graphite/Carbon Anode	8.2	7.9	7.8	7.7
Silicon	0.0	0.0	0.0	0.0
Binder (polyvinylidene fluoride, or PVDF)	0.4	0.4	0.4	0.4
Copper	24.7	24.5	24.0	24.2
Wrought Aluminum	25.7	25.4	25.1	25.0
Cast Aluminum	0.0	0.0	0.0	0.0
$LiPF_6$	0.9	0.9	1.0	1.0
Ethylene Carbonate	2.6	2.6	2.7	2.7
Dimethyl Carbonate	2.6	2.6	2.7	2.7
PP	1.1	1.1	1.1	1.1
Polyethylene (PE)	0.6	0.6	0.6	0.6
PET	0.3	0.3	0.3	0.3
Steel	0.7	0.7	0.7	0.7
Thermal Insulation	1.6	1.6	1.5	1.5
Glycol	12.5	12.1	11.9	11.6
Electronic Parts (battery management system, or BMS)	6.8	6.6	6.3	6.2

Table 37 Material composition of Li-ion batteries in Class 6 PnD trucks (EV) (%)

Materials	Material Composition (wt.%)		
	NMC811	NMC622	NMC532
Cathode (active material)	20.4	22.9	24.9
Graphite/Carbon Anode	14.7	14.0	13.6
Silicon	0.0	0.0	0.0
Binder (PVDF)	0.7	0.8	0.8
Copper	16.4	15.7	15.2
Wrought Aluminum	31.4	30.5	29.7
Cast Aluminum	0.0	0.0	0.0
$LiPF_6$	1.1	1.1	1.1
Ethylene Carbonate	3.0	3.0	3.0
Dimethyl Carbonate	3.0	3.0	3.0
PP	1.2	1.2	1.1
PE	0.5	0.5	0.5
PET	0.2	0.2	0.2
Steel	0.1	0.1	0.1
Thermal Insulation	0.8	0.7	0.7
Glycol	6.0	5.8	5.7
Electronic Parts (BMS)	0.5	0.5	0.5

Table 38 Material composition of Li-ion batteries in Class 6 PnD trucks (FCV) (%)

Materials	Material Composition (wt.%)			
	NMC811	NMC622	NMC532	NMC111
Cathode (active material)	11.8	13.3	14.7	15.0
Graphite/Carbon Anode	8.7	8.4	8.3	8.1
Silicon	0.0	0.0	0.0	0.0
Binder (PVDF)	0.4	0.4	0.5	0.5
Copper	26.1	25.8	25.4	25.5
Wrought Aluminum	25.0	24.7	24.3	24.3
Cast Aluminum	0.0	0.0	0.0	0.0
$LiPF_6$	1.0	1.0	1.0	1.0
Ethylene Carbonate	2.7	2.8	2.9	2.9
Dimethyl Carbonate	2.7	2.8	2.9	2.9
PP	1.2	1.2	1.2	1.2
PE	0.6	0.6	0.6	0.6
PET	0.3	0.3	0.3	0.3
Steel	0.7	0.7	0.7	0.7
Thermal Insulation	1.7	1.6	1.6	1.6
Glycol	10.9	10.5	10.2	10.0
Electronic Parts (BMS)	6.1	5.8	5.6	5.5

Table 39 Material composition of Li-ion batteries in Class 8 day-cab trucks (HEV) (%)

Materials	Material Composition (wt.%)			
	NMC811	NMC622	NMC532	NMC111
Cathode (active material)	12.5	13.3	14.6	14.9
Graphite/Carbon Anode	9.2	8.3	8.2	8.0
Silicon	0.0	0.0	0.0	0.0
Binder (PVDF)	0.4	0.4	0.5	0.5
Copper	27.0	25.1	24.6	24.7
Wrought Aluminum	24.4	28.2	27.8	27.7
Cast Aluminum	0.0	0.0	0.0	0.0
$LiPF_6$	1.0	1.0	1.0	1.0
Ethylene Carbonate	2.9	2.8	2.8	2.8
Dimethyl Carbonate	2.9	2.8	2.8	2.8
PP	1.2	1.2	1.1	1.1
PE	0.6	0.5	0.5	0.5
PET	0.3	0.3	0.3	0.3
Steel	0.7	0.6	0.6	0.6
Thermal Insulation	1.7	1.7	1.7	1.7
Glycol	9.6	8.7	8.6	8.5
Electronic Parts (BMS)	5.5	5.0	4.8	4.7

Table 40 Material composition of Li-ion batteries in Class 8 day-cab trucks (EV) (%)

Materials	Material Composition (wt.%)		
	NMC811	NMC622	NMC532
Cathode (active material)	26.2	29.1	31.3
Graphite/Carbon Anode	18.2	17.2	16.6
Silicon	0.0	0.0	0.0
Binder (PVDF)	0.9	0.9	1.0
Copper	17.1	16.2	15.6
Wrought Aluminum	22.9	22.1	21.4
Cast Aluminum	0.0	0.0	0.0
$LiPF_6$	1.3	1.3	1.3
Ethylene Carbonate	3.7	3.7	3.7
Dimethyl Carbonate	3.7	3.7	3.7
PP	1.4	1.4	1.3
PE	0.4	0.4	0.4
PET	0.2	0.2	0.2
Steel	0.1	0.1	0.1
Thermal Insulation	0.6	0.6	0.5
Glycol	3.1	3.0	2.9
Electronic Parts (BMS)	0.2	0.2	0.2

Table 41 Material composition of Li-ion batteries in Class 8 day-cab trucks (FCV) (%)

Materials	Material Composition (wt.%)			
	NMC811	NMC622	NMC532	NMC111
Cathode (active material)	13.7	15.4	16.9	17.2
Graphite/Carbon Anode	9.9	9.5	9.3	9.1
Silicon	0.0	0.0	0.0	0.0
Binder (PVDF)	0.5	0.5	0.5	0.5
Copper	26.2	25.7	25.2	25.1
Wrought Aluminum	26.8	26.3	25.9	25.8
Cast Aluminum	0.0	0.0	0.0	0.0
$LiPF_6$	1.1	1.1	1.1	1.1
Ethylene Carbonate	3.0	3.1	3.1	3.1
Dimethyl Carbonate	3.0	3.1	3.1	3.1
PP	1.2	1.2	1.1	1.1
PE	0.5	0.5	0.5	0.5
PET	0.3	0.3	0.3	0.3
Steel	0.6	0.6	0.6	0.6
Thermal Insulation	1.8	1.7	1.7	1.7
Glycol	7.3	6.9	6.7	6.7
Electronic Parts (BMS)	4.2	4.0	3.9	3.8

Table 42 Material composition of Li-ion batteries in Class 8 sleeper-cab trucks (HEV) (%)

Materials	Material Composition (wt.%)			
	NMC811	NMC622	NMC532	NMC111
Cathode (active material)	12.5	13.3	14.6	14.9
Graphite/Carbon Anode	9.2	8.3	8.2	8.0
Silicon	0.0	0.0	0.0	0.0
Binder (PVDF)	0.4	0.4	0.5	0.5
Copper	27.0	25.1	24.6	24.7
Wrought Aluminum	24.4	28.2	27.8	27.7
Cast Aluminum	0.0	0.0	0.0	0.0
$LiPF_6$	1.0	1.0	1.0	1.0
Ethylene Carbonate	2.9	2.8	2.8	2.8
Dimethyl Carbonate	2.9	2.8	2.8	2.8
PP	1.2	1.2	1.1	1.1
PE	0.6	0.5	0.5	0.5
PET	0.3	0.3	0.3	0.3
Steel	0.7	0.6	0.6	0.6
Thermal Insulation	1.7	1.7	1.7	1.7
Glycol	9.6	8.7	8.6	8.5
Electronic Parts (BMS)	5.5	5.0	4.8	4.7

Table 43 Material composition of Li-ion batteries in Class 8 sleeper-cab trucks (EV) (%)

Materials	Material Composition (wt.%)		
	NMC811	NMC622	NMC532
Cathode (active material)	28.2	31.2	33.4
Graphite/Carbon Anode	19.4	18.3	17.6
Silicon	0.0	0.0	0.0
Binder (PVDF)	1.0	1.0	1.0
Copper	17.1	16.1	15.4
Wrought Aluminum	19.9	19.1	18.5
Cast Aluminum	0.0	0.0	0.0
$LiPF_6$	1.4	1.4	1.4
Ethylene Carbonate	3.9	3.9	3.9
Dimethyl Carbonate	3.9	3.9	3.9
PP	1.5	1.4	1.4
PE	0.4	0.4	0.4
PET	0.2	0.2	0.2
Steel	0.1	0.1	0.1
Thermal Insulation	0.5	0.5	0.5
Glycol	2.4	2.3	2.2
Electronic Parts (BMS)	0.1	0.1	0.1

Table 44 Material composition of Li-ion batteries in Class 8 sleeper-cab trucks (FCV) (%)

Materials	Material Composition (wt.%)			
	NMC811	NMC622	NMC532	NMC111
Cathode (active material)	12.9	14.5	15.9	16.2
Graphite/Carbon Anode	9.3	8.9	8.8	8.6
Silicon	0.0	0.0	0.0	0.0
Binder (PVDF)	0.5	0.5	0.5	0.5
Copper	26.8	26.4	25.8	25.9
Wrought Aluminum	27.2	26.9	26.4	26.3
Cast Aluminum	0.0	0.0	0.0	0.0
$LiPF_6$	1.0	1.1	1.1	1.1
Ethylene Carbonate	2.9	3.0	3.0	3.1
Dimethyl Carbonate	2.9	3.0	3.0	3.1
PP	1.2	1.2	1.2	1.2
PE	0.5	0.5	0.5	0.5
PET	0.3	0.3	0.3	0.3
Steel	0.6	0.6	0.6	0.6
Thermal Insulation	1.8	1.8	1.7	1.7
Glycol	7.5	7.2	7.0	6.9
Electronic Parts (BMS)	4.4	4.2	4.0	4.0

Regarding Pb-acid batteries, the number of these batteries needed for various MHDVs is taken from literature (Interstate Batteries, 2021; Tomic et al., 2014) and provided in Table 45. Briefly, all MHDVs are assumed to use at least one Pb-acid battery for initial startup requirement, as per literature (Interstate Batteries, 2021; Tomic et al., 2014), with more of these batteries employed in ICEV and HEV MHDVs to meet accessory loads. Based on the above-mentioned information and other inputs, battery material composition (extended from the GREET® model for LDVs) is provided in Table 46. Battery weights (for all batteries) are obtained for chosen MHDVs from literature for Pb-acid batteries (Interstate Batteries, 2021) and from BatPaC 4.0 for Li-ion batteries and are given in Tables 47–49.

Table 45 Number of Pb-acid batteries used for MHDVs with different propulsion technologies

Type of MHDV	ICEV	HEV	EV	FCV
Class 6 PnD	2	2	1	1
Class 8 Day-cab	3	2	1	1
Class 8 Sleeper-cab	4	3	1	1
Weight of 1 Pb-acid battery: 69 lbs. (Interstate Batteries, 2021)				

Table 46 Material composition of Pb-acid batteries in MHDVs

Materials	Material Composition (wt.%)
PP	6.1
Lead	69.0
Sulfuric Acid	7.9
Fiberglass	2.1
Water	14.1
Others	0.8

Table 47 Battery weight for Class 6 PnD trucks (lbs.)

Battery Type	Battery Chemistry	ICEV	HEV	EV	FCV
Pb-acid		138	138	69	69
Li-ion	NMC811	N/A	125	3,554	141
	NMC622	N/A	131	3,729	147
	NMC532	N/A	136	3,945	153
	NMC111	N/A	137	N/A	155
N/A = Not applicable					

Table 48 Battery weight for Class 8 day-cab trucks (lbs.)

Battery Type	Battery Chemistry	ICEV	HEV	EV	FCV
Pb-acid		207	138	69	69
Li-ion	NMC811	N/A	155	9,667	203
	NMC622	N/A	172	10,243	212
	NMC532	N/A	179	10,928	222
	NMC111	N/A	182	N/A	226
N/A = Not applicable					

Table 49 Battery weight for Class 8 sleeper-cab trucks (lbs.)

Battery Type	Battery Chemistry	ICEV	HEV	EV	FCV
Pb-acid		276	207	69	69
Li-ion	NMC811	N/A	155	16,030	194
	NMC622	N/A	172	17,039	203
	NMC532	N/A	179	18,229	212
	NMC111	N/A	182	N/A	215
N/A = Not applicable					

3.7 Battery Replacement and Recycling

A critical factor in determining battery-related energy use and emissions over the lifetime of a MHDV is the number of times it has to be replaced in this duration. For all the MHDVs considered in this study, this depends on the nature of batteries employed (related to the propulsion technology used) and the distance traveled by them between two battery replacements.

Among the considered battery technologies, Pb-acid batteries present the highest degree of certainty given the highly mature state of this technology. These batteries are typically replaced every four years for freight trucks, irrespective of the propulsion technology employed (Lowell, 2018). Hence, the battery replacement interval for Pb-acid batteries in MHDVs is obtained by multiplying this duration with their respective annual distance traveled, as provided by the U.S. Transportation Energy Data Book 2021 (Davis & Boundy, 2021). Note that users can change this replacement schedule by modifying the number of Pb-acid battery replacements for each of the considered MHDVs. Further, Pb-acid batteries enjoy high recycling rates (~99%) and use a high amount of recycled lead and plastic content (Illinois Sustainable Technology Center & U.S. EPA Office of Solid Waste, 2015; U.S. EPA, 2020) — an aspect that is also considered earlier in the GREET® model for LDVs (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006) and is extended here to MHDVs.

In contrast to Pb-acid, there is less certainty for Li-ion battery replacement, which is mainly due to the limited amount of publicly available research data on the performance of these batteries in freight trucks. However, a few studies suggest that EV MHDVs will require Li-ion batteries to be replaced anywhere around 400,000–500,000 miles (Sen et al., 2017, 2019). Hence, the default assumption here is that Li-ion batteries will last for the entire lifetime of Class 6 EV MHDVs but will be replaced once over the total lifetime of Class 8 EV MHDVs (day-cab and sleeper-cab). Users are provided the option to modify this assumption and provide the desired number of replacements for these batteries.

3.8 Fuel Stack Replacement

Similar to the case of batteries, there is limited information on the ability of fuel stacks to last over the entire lifetime of MHDVs, especially for Class 8 trucks. Nevertheless, the user is provided the option to account for any replacement in fuel-cell stacks over the lifetime of all chosen MHDVs and assess its effect on the impacts of fuel-cell MHDVs over their vehicle-cycle and life-cycle. The default option chosen in this study is no replacement of fuel-cell stacks over the lifetime of all fuel-cell MHDVs.

3.9 Replacements of Components: Tire, Fluids, Fuel Stacks, and Others

Apart from batteries and fuel-cell stacks, other subsystems/individual parts are also replaced during the lifetime of a freight truck. Here, four such parts/subsystems are considered: tires, fluids, engine oil filters, and windshield wiper blades. Since the number of replacements for all these parts depends on the total lifetime of MHDVs, the total lifetime is considered as 300,000 miles for Class 6 PnD trucks (Clinton, 2015; Davis & Boundy, 2021; Penske Used Trucks, 2021) and 1 million miles for Class 8 (day-cab and sleeper-cab) trucks (Marcinkoski et al., 2019; U.S. DOE, 2013).

Unlike LDVs, the tires used in MHDVs are of three types: (a) steer tires; (b) drive tires; and (c) trailer tires (used for trailers fitted to Class 8 truck tractors). This study assumes different lifetimes for these three sets of tires for the chosen truck options based on industry literature, as shown in Table 50. These lifetimes (in terms of replacements) are coupled with the tire material composition — assumed to be the same as that for LDVs in GREET® at 67% rubber and 33% steel (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006) — to obtain the total use of these materials for tires over the MHDV lifetime. Like for LDVs, the last set of tires (of either type) are considered to be scrapped with none of the tires being reused for any truck due to safety concerns.

Table 50 Lifetime of MHDV tires

Type of MHDV	Lifetime (miles)			References
	Steer Tires	Drive Tires	Trailer Tires	
Class 6 PnD	125,000	200,000		(Kilcarr, 2006)
Class 8 Day-cab	125,000	275,000	95,000	
Class 8 Sleeper-cab	125,000	275,000	95,000	

Multiple fluids are used in MHDVs (including trailers) for routine maintenance at varying intervals. Several assumptions have been made about the lifetime of these fluids for MHDVs across various propulsion technologies, based on existing literature — these assumptions are provided in Tables 51–52. Additional assumptions about these fluids, including their individual material composition, are extended from Argonne's previous work on GREET® for LDVs (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006) and are given in Table 53. In addition, the mass of fluids used for different MHDVs are provided in Tables 54–57. For engine oil filters (used in ICEV and HEV MHDVs) and windshield wiper blades, their respective lifetimes (in terms of years and/or distance traveled) are given in Table 58.

Table 51 Lifetime of MHDV fluids (miles)

Type of Fluid	Type of MHDV (lifetime in miles)			References
	Class 6 PnD	Class 8 Day-cab	Class 8 Sleeper-cab	
Engine Oil	30,000	50,000	50,000	(Cummins, 2021)
Steer Axle Lubricant	25,000	25,000	25,000	(Dana Spicer, 2019)
Drive Axle Lubricant	500,000	500,000	500,000	
Inter-axle Shaft/Driveshaft Lubricant	25,000	350,000 for 1st cycle; 100,000 for subsequent cycles	350,000 for 1st cycle; 100,000 for subsequent cycles	
Lubricant: Wheel-ends at Steer Axle	500,000	500,000	500,000	
Lubricant: Wheel-ends at Drive Axle	500,000	500,000	500,000	
Transmission Fluid	75,000	500,000	500,000	(Eaton, 2018)
Engine/Powertrain Coolant	150,000	932,057	932,057	(Cummins Filtration, 2021)
Coolant Cleaner	Same as engine/powertrain coolant			
Windshield Fluid (lifetime = 6 months)	5,844	31,687	65,250	(Auto Zone Inc., 2021)

Table 52 Lifetime of trailer fluids (miles)

Type of Fluid	Lifetime (miles)	References
Trailer Axle Lubricant	500,000	(Dana Ltd., 2021; Dana Ltd. & Dana Spicer, 2021)
Lubricant: Wheel-ends at Trailer Axle	500,000	

Table 53 Major assumptions regarding all vehicle fluids (including trailer)

<table>
<tr><th>Type of Fluid</th><th>Key Assumptions</th></tr>
<tr><td>Engine Oil</td><td rowspan="5">• Material composition, energy use, and emissions (on per-lbs. basis) extended from similar fluids used in LDVs in GREET®
• Actual amount of use and replacement schedule considered from literature (bottom-up approach)</td></tr>
<tr><td>Power Steering Fluid</td></tr>
<tr><td>Brake Fluid</td></tr>
<tr><td>Windshield Fluid</td></tr>
<tr><td>Adhesives</td></tr>
<tr><td>Transmission Fluid</td><td rowspan="2">• Material composition, energy use, and emissions (on per-lbs. basis) extended from similar fluids used in LDVs in GREET®
• Actual amount of use and replacement schedule considered from literature (bottom-up approach)
• Ratio of fluid use in HEV/EV/FCV MHDV to ICEV MHDV assumed to be the same as that for fluid use in HEV/EV/FCV LDV to ICEV LDV</td></tr>
<tr><td>Engine/Powertrain Coolant</td></tr>
<tr><td>Steer Axle Lubricant</td><td rowspan="8">• Material composition, energy use, and emissions (on per-lbs. basis) assumed to be the same as that for engine oil used in LDVs in GREET®
• Actual amount of use and replacement schedule considered from literature (bottom-up approach)</td></tr>
<tr><td>Drive Axle Lubricant</td></tr>
<tr><td>Inter-axle Shaft/Driveshaft Lubricant</td></tr>
<tr><td>Lubricant: Wheel-ends at Steer Axle</td></tr>
<tr><td>Lubricant: Wheel-ends at Drive Axle</td></tr>
<tr><td>Coolant Cleaner</td></tr>
<tr><td>Trailer Axle Lubricant</td></tr>
<tr><td>Lubricant: Wheel-ends at Trailer Axle</td></tr>
</table>

Table 54 Amount of fluids used per use cycle in ICEV MHDVs

Type of Fluid	Weight of Fluids Used (lbs.): ICEV		
	Class 6 PnD	Class 8 Day-cab	Class 8 Sleeper-cab
Engine Oil	33.7	92.2	92.2
Steer Axle Lubricant	15.4	15.4	15.4
Drive Axle Lubricant	12.9	45.2	45.2
Inter-axle Shaft/Driveshaft Lubricant	30.9	30.9	30.9
Lubricant: Wheel-ends at Steer Axle	19.0	19.0	19.0
Lubricant: Wheel-ends at Drive Axle	19.0	38.0	38.0
Power Steering Fluid	0.0	0.0	0.0
Brake Fluid	0.0	0.0	0.0
Transmission Fluid	16.9	14.1	14.1
Engine/Powertrain Coolant	54.1	121.1	121.1
Coolant Cleaner	55.1	55.1	55.1
Windshield Fluid	15.9	15.9	15.9
Trailer Axle Lubricant	N/A	45.2	45.2
Lubricant: Wheel-ends at Trailer Axle	N/A	38.0	38.0
N/A = Not applicable			

Table 55 Amount of fluids used per use cycle in HEV MHDVs

Type of Fluid	Weight of Fluids Used (lbs.): HEV		
	Class 6 PnD	Class 8 Day-cab	Class 8 Sleeper-cab
Engine Oil	33.7	92.2	92.2
Steer Axle Lubricant	15.4	15.4	15.4
Drive Axle Lubricant	12.9	45.2	45.2
Inter-axle Shaft/Driveshaft Lubricant	30.9	30.9	30.9
Lubricant: Wheel-ends at Steer Axle	19.0	19.0	19.0
Lubricant: Wheel-ends at Drive Axle	19.0	38.0	38.0
Power Steering Fluid	0.0	0.0	0.0
Brake Fluid	0.0	0.0	0.0
Transmission Fluid	5.2	2.2	2.2
Engine/Powertrain Coolant	54.1	121.1	121.1
Coolant Cleaner	55.1	55.1	55.1
Windshield Fluid	15.9	15.9	15.9
Trailer Axle Lubricant	N/A	45.2	45.2
Lubricant: Wheel-ends at Trailer Axle	N/A	45.2	45.2
N/A = Not applicable			

Table 56 Amount of fluids used per cycle in EV MHDVs

Type of Fluid	Weight of Fluids Used (lbs.): EV		
	Class 6 PnD	Class 8 Day-cab	Class 8 Sleeper-cab
Engine Oil	0.0	0.0	0.0
Steer Axle Lubricant	15.4	15.4	15.4
Drive Axle Lubricant	12.9	45.2	45.2
Inter-axle Shaft/Driveshaft Lubricant	30.9	30.9	30.9
Lubricant: Wheel-ends at Steer Axle	19.0	19.0	19.0
Lubricant: Wheel-ends at Drive Axle	19.0	38.0	38.0
Power Steering Fluid	0.0	0.0	0.0
Brake Fluid	0.0	0.0	0.0
Transmission Fluid	5.2	2.2	2.2
Engine/Powertrain Coolant	37.1	83.0	83.0
Coolant Cleaner	37.8	37.8	37.8
Windshield Fluid	15.9	15.9	15.9
Trailer Axle Lubricant	N/A	45.2	45.2
Lubricant: Wheel-ends at Trailer Axle	N/A	45.2	45.2
N/A = Not applicable			

Table 57 Amount of fluids used per cycle in FCV MHDVs

Type of Fluid	Weight of Fluids Used (lbs.): FCV		
	Class 6 PnD	Class 8 Day-cab	Class 8 Sleeper-cab
Engine Oil	0.0	0.0	0.0
Steer Axle Lubricant	15.4	15.4	15.4
Drive Axle Lubricant	12.9	45.2	45.2
Inter-axle Shaft/Driveshaft Lubricant	30.9	30.9	30.9
Lubricant: Wheel-ends at Steer Axle	19.0	19.0	19.0
Lubricant: Wheel-ends at Drive Axle	19.0	38.0	38.0
Power Steering Fluid	0.0	0.0	0.0
Brake Fluid	0.0	0.0	0.0
Transmission Fluid	5.2	2.2	2.2
Engine/Powertrain Coolant	37.1	83.0	83.0
Coolant Cleaner	37.8	37.8	37.8
Windshield Fluid	15.9	15.9	15.9
Trailer Axle Lubricant	N/A	45.2	45.2
Lubricant: Wheel-ends at Trailer Axle	N/A	45.2	45.2
N/A = Not applicable			

Table 58 Lifetime of frequently replaced MHDV parts (years/miles)

MHDV Parts	Lifetime (years/miles)	References
Windshield Wiper Blades	1 year	(Auto Zone, 2021)
Engine Oil Filters (changed along with engine oil)	Same as engine oil	(Cummins, 2021)

3.10 Limitations

In addition to the lack of vehicle inventory from a single source, there are also other limitations associated with this MHDV inventory development. The first is the extension of several parameters used for LDVs in GREET® to MHDVs examined here due to the lack of alternative data in our literature review. This includes the: (a) weight share of virgin and recycled content for different materials, such as steel, wrought aluminum, and cast aluminum; (b) energy use and emissions associated with various vehicle fluids, including those used specifically in MHDVs; (c) weight composition of different plastics in the average plastic used; and (d) material composition of traction motor, generator, electronic controller, vehicle fluids, and Pb-acid battery. In addition, the lack of any inventory details for multiple materials, including those specifically used in MHDVs (such as wood, damask fiber, and niobium), as well as those used in MHDVs and LDVs (like titanium and chromium) in the GREET® model, meant that energy and emission values associated with these elements is 0, i.e., their contributions cannot be considered. Nevertheless, the small amount of use of these elements across all MHDVs means that these elements are not expected to drastically change the vehicle-cycle energy use and emissions for the considered MHDVs.

4 VEHICLE ASSEMBLY, DISPOSAL, AND RECYCLING

This analysis utilizes the past data on energy use and emissions associated with the assembly, painting, disposal, and recycling processes for the MHDVs (the entire Class 6 PnD truck and both the tractor and trailer for Class 8 trucks). Hence, barring the recycling of MHDVs, energy consumption and emissions of various constituent ADR processes are assumed to be the same as for these processes in the GREET® model for LDVs (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006). For vehicle recycling, the amount of energy use and emissions is scaled-up from the LDV model to fit the MHDV mass. Like for LDVs, this energy use (or associated emissions) does not include any of the material recovery process or combustion processes associated with energy recovery; instead, energy use of materials that are recycled (reprocessed) for use in MHDVs is considered separately within the GREET® model.

Regarding battery assembly and testing of both Pb-acid batteries (on per-lb. basis) and Li-ion batteries (on per-kWh basis), data for their energy use and emissions are extended from the GREET® model for LDVs (Argonne National Laboratory, 2020; Burnham, 2012; Burnham et al., 2006). Table 59 shows the amount of energy consumed for different constituent ADR processes for trucks, trailers, and batteries, along with their corresponding units.

Table 59 Energy use associated with vehicle and battery ADR processes

Constituent ADR Process	Energy Consumed	Unit
Paint Production	0.287	mmBtu per vehicle/trailer
Painting	2.759	
HVAC and Lighting	0.99	
Heating	2.982	
Material Handling	0.205	
Welding	0.273	
Compressed Air	0.409	
Disposal/Recycling	0.00047 × weight (weight = weight of MHDV/trailer)	
Pb-acid Battery Assembly	2.300	mmBtu per lb.
Li-ion Battery Assembly	0.161	mmBtu per kWh

5 GREET2 MODEL STRUCTURE EXPANSION FOR MHDVS

The following sections introduce the additional working sheets incorporated in the updated version of the GREET2 model. The sheets are all related specifically to MHDV profiles and auxiliary calculation processes. In general, the sheets are modeled using the same basis as the LDV sheets to retain coherence for users.

5.1 MHDV_Inputs Sheet

This sheet is separated into nine sections:

1. Selection of truck types for simulation (as input).
2. Specification of total truck weight.
3. Truck battery and fluids weight.
4. Key input parameters for truck components: body, powertrain system, transmission system, chassis, traction motor, generator, electronic controller, and fuel-cell auxiliary system.
5. Key input parameters for batteries, fuel stacks, and hydrogen tanks.
6. Key input parameters for fluids and repeatedly replaced components.
7. GREET® default key assumptions for truck/trailer ADR.
8. Lifetime vehicle miles traveled of MHDVs and trailers.
9. Trailers.

Like for LDVs, this sheet provides key variables for vehicle-cycle scenarios and specifies important parametric assumptions for MHDVs and their components for subsequent calculations in GREET2 (regarding total energy use and various emissions).

In the MHDV_Inputs sheet, the first section (Section 1) allows the user to specify the truck option (Class 6 PnD, Class 8 day-cab, or Class 8 sleeper-cab truck), for which energy use and emissions are to be calculated. Next, Section 2 inputs the total weight of the concerned truck to be simulated (taken from the individual sheets for each chosen truck option, described in Section 5.3). Similarly, Section 3 takes the weight of Pb-acid and Li-ion batteries for each propulsion technology as inputs from the individual truck option-based sheets (see Section 5.3).

In Section 4, the weight of all MHDV components (excluding batteries, fluids, and fuel) is provided for each propulsion technology for the specific chosen MHDV. This section also provides the power sizing of fuel-cell stack (in kW), followed by its weight-to-power ratio (lbs./kW) and the overall weight of fuel-cell stacks and auxiliary components (hydrogen tanks). For all MHDVs, this section gives the detailed break-up of weight and weight share (wt.%) for all the component categories included in this section. Additionally, it gives the values for the number of replacements, as well as the number of components, used per use-cycle (during operation) for tires, windshield wiper blades, and engine oil filters, along with the weight of vehicle tires.

Section 5 details key input parameters for batteries, including the choice of Li-ion battery cathode chemistry (NMC811, NMC622, NMC532, and NMC111), the size of battery (energy/power) for various propulsion technologies, the number of battery replacements over MHDV lifetime, and the value of specific power and energy for Li-ion batteries for various MHDVs. Additionally, this section gives the user the choice to select pressure (700 bar or 350 bar) for the hydrogen tank of FCV trucks for the concerned truck option. The section also allows for specifying the number of fuel-cell stack replacements during the lifetime of FCV MHDVs (with the default value being 0).

Section 6 allows the user to focus on key inputs for fluids, including the number of replacements for various fluids as well as the ratio of waste-to-product for their disposal. Section 7 gives the default key assumptions for energy use during battery assembly (for various batteries used in trucks) and during the vehicle assembly, painting, disposal, and recycling (ADR) phase. Subsequently, Section 8 provides the lifetime of the truck in terms of miles (and not years).

Finally, Section 9 represents the important focal point of the difference between GREET® sheets for LDVs and freight trucks, for this section contains inputs on trailers used in Class 8 trucks. Apart from the number of trailer tires and the frequency of their replacement over a truck's lifetime, it also provides data on trailer tire weight, trailer vehicle fluids (quantity used per cycle and number of replacement cycles), and trailer weight composition (overall weight and weight share of different trailer parts, namely, trailer body, chassis, and auxiliary parts). In addition, this section provides energy use values for ADR processes associated with trailers.

5.2 MHDV_Mat_Parameters Sheet

This sheet is separated into three sections:

1. Material composition for truck components.
2. Battery material composition.
3. Material composition for trailer components.

For all the three sections of MHDV_Mat_Parameters sheet, the values depend on the type of MHDV (Class 6 PnD, Class 8 day-cab, or Class 8 sleeper-cab) chosen. Section 1 shows the material break-up of all component systems listed in Table 2, as well as the aggregate material composition of the concerned MHDV. In addition, it also gives the material composition of tires (extended from LDVs) and individual parts that are frequently replaced (windshield wiper blades and engine oil filters). Section 2 gives details on the material composition of Pb-acid and Li-ion batteries (inclusive of all the Li-ion battery chemistries). Lastly, Section 3 gives information on the material composition of the trailer component groups/systems and of the entire trailer.

5.3 Class 6 PnD Trucks, Class 8 Day-cab Trucks, and Class 8 Sleeper-cab Trucks Sheets

These three sheets are organized on similar lines and contain all the inputs for their respective MHDVs. These inputs are then used in MHDV_Inputs and MHDV_Mat_Parameters sheets, based on the MHDV chosen in MHDV_Inputs sheet.

5.4 MHDV_Fluids Sheet

This worksheet consists of the following five sections:

1. Key input parameters: The values in this section are derived from the MHDV_Inputs sheet and then manipulated/processed to calculate the energy use and emissions associated with vehicle fluids used in MHDVs (excluding trailers).

2. Shares of combustion processes for each stage: These are used to calculate emissions.

3. Calculation of energy consumption and emissions for each stage: Here, GREET2 calculates the energy use and emissions for each individual vehicle fluid, considering the fuel use by type, combustion technology, energy efficiency, and other aspects.

4. Summary of energy consumption and emissions related to fluids: This involves significant parameters that are used later for per-vehicle lifetime calculations.

5. Per-vehicle lifetime energy consumption and emissions of fluids: Here, energy use and emissions are calculated on per-vehicle lifetime basis and are subsequently used to determine vehicle-cycle energy use and emissions in other sheets.

Here, energy use and emission calculations are undertaken for multiple fluids that are used in MHDVs. These include engine oil, powertrain coolant, coolant cleaner, windshield fluid, power steering fluid, brake fluid, transmission fluid, adhesives, and lubrication oil (used in steer and drive axles, inter-axle shaft, driveshaft, and wheel-ends at steer and drive axles). The weight of each fluid (on per-vehicle basis) and the number of replacements per MHDV lifetime are already defined in the MHDV_Inputs sheet, while for each fluid, the waste-to-product ratio is taken from the MHDV_Inputs sheet (which is in turn derived from the concerned MHDV sheet, described in Section 5.3). These waste-to-product ratio values are in turn extended from LDVs to MHDVs.

5.5 MHDV_Trailer_Fluids Sheet

This worksheet consists of the following five sections:

1. Key input parameters: The values in this section are derived from the MHDV_Inputs sheet and then manipulated/processed to calculate energy use and emissions associated with the fluids used in trailers.

2. Shares of the combustion processes for each stage: These are used to calculate emissions.

3. Calculation of energy consumption and emissions for each stage: GREET2 calculates the energy use and emissions for each individual process, considering the fuel use by type, combustion technology, energy efficiency, and other aspects.

4. Summary of energy consumption and emissions related to fluids: This involves key parameters that are used for per-vehicle lifetime calculations.

5. Per-vehicle lifetime energy consumption and emissions of fluids: Here, energy use and emissions are calculated on per-vehicle lifetime basis and are subsequently used for vehicle-cycle-related calculations in other sheets.

Here, energy use and emission calculations are undertaken for lubrication oils used in trailer axles and trailer wheel-ends.

5.6 MHDV_ADR Sheet

This worksheet, modeled off the Vehi_ADR sheet for LDVs, consists of four sections:

1. Key input parameters: This section provides the share of different types for various materials, including the extent of recycled material content, that are used in different MHDVs, extending these shares from LDVs.

2. Shares of combustion processes for each stage: These are used to calculate emissions.

3. Calculations of energy consumption and emissions for each stage: This is done for individual stages associated with truck assembly, painting, disposal, and recycling, keeping in mind factors associated with fuel use by type, combustion technology, and energy efficiency.

4. Summary of energy consumption and emissions for ADR processes on per-vehicle basis: This is used in subsequent vehicle-cycle calculations in other GREET2 sheets.

5.7 MHDV_Trailer_ADR Sheet

This worksheet is modeled off the MHDV_ADR sheet (described in Section 5.6) with the exact same sections as in MHDV_ADR sheet (coupled with the descriptions). The same key input parameters are used as those for LDVs, considering the paucity of data availability on this aspect for trailers used in Class 8 trucks.

5.8 MHDV_Battery_Sum Sheet

This worksheet, modeled off the Battery_Sum sheet for LDVs, consists of three sections:

1. Key input parameters: Input values from MHDV_Inputs and MHDV_Mat_Parameters sheets are taken here for further processing.

2. Calculation of energy consumption and emissions for each battery type on per-vehicle lifetime: Energy use and emissions of each battery (Pb-acid and Li-ion) for different propulsion technologies are calculated using their respective material composition and material-based energy use and emissions from the Mat_Sum sheet.

3. Summary of energy consumption and emissions: Calculations on battery-related energy use and emissions are summarized here and used subsequently for vehicle-cycle-related calculations in other GREET2 sheets. While the type of battery used in HEV and FCV MHDVs, along with peak battery output, number of battery replacements, specific power of battery, and their weight are defined in the MHDV_Inputs sheet, the material composition of batteries is given in the MHDV_Mat_Parameters sheet.

5.9 MHDV_Comp_Sum Sheet

This worksheet is modeled off the Vehi_Comp_Sum sheet (used for LDVs) and consists of three sections:

1. Key input parameters: The parameters are derived from MHDV_Inputs and MHDV_Mat_Parameters sheet and are processed further here.

2. Summary of energy consumption and emissions for vehicle materials on per-vehicle lifetime: The weight of each material in each vehicle component system is given along with the energy used and emissions for all components/systems in each MHDV over the entire MHDV lifetime.

3. Summary of energy consumption and emissions by vehicle component (per-vehicle lifetime): Energy use and emissions are disaggregated by each component system in the concerned MHDV over its lifetime.

5.10 MHDV_Trailer_Comp_Sum Sheet

This worksheet, similar to the MHDV_Comp_Sum sheet for MHDVs, consists of two sections:

1. Key input parameters: These input values are taken from MHDV_Inputs and MHDV_Mat_Parameters sheet and are processed further here.

2. Summary of energy consumption and emissions for trailer materials (per-trailer lifetime): Here, energy use and emissions are disaggregated by each trailer component system and then totaled to obtain the overall value for the entire trailer lifetime (assumed to be the same as MHDV lifetime).

5.11 MHDV_Sum Sheet

This worksheet, modeled off the Vehi_Sum sheet for LDVs, consists of three sections:

1. Summary of energy consumption and emissions per vehicle lifetime: Energy use and emissions are displayed for MHDV truck components, ADR, batteries, fluids, and trailers, and these are totaled to obtain the overall vehicle-cycle energy use and emissions for all MHDVs.

2. Summary of energy consumption and emissions of vehicle-cycle per mile: Here, vehicle-cycle energy use and emissions for each MHDV are converted to per-mile results.

3. Vehicle-cycle energy and emissions changes: Vehicle-cycle energy use and emissions are shown as percentages relative to ICEV.

5.12 MHDV_TEC_Results Sheet

This worksheet consists of two sections:

1. Well-to-pump, vehicle-cycle, and vehicle-operation energy use and emissions: Here, fuel-cycle (well-to-pump) and vehicle-operation values are obtained from GREET1 (imported in GREET1_Import_Export sheet in the GREET2 workbook), while vehicle-cycle results are calculated here and added up to estimate the total life-cycle results for each MHDV.

2. Well-to-pump, vehicle-cycle, and vehicle-operation energy and emissions changes: Here, total life-cycle energy use and emissions of different propulsion technologies are shown as percentages relative to the conventional diesel-based ICEV MHDV.

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